Characterization of Brazed Joints on Threaded X52 Steel Pipe Connections

Masters Thesis

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Abstract

The new technology of expanded tubular (cold worked pipes), for application in the oil and gas industry is of considerable interest. It is important to devise reliable testing techniques that are able to determine the mechanical properties of the pipe joints made under specific geometrical and mechanical conditions. It is also important to evaluate the metallurgical characteristics of the filler metals in the joints (e.g., existing phases and morphology) that determine such mechanical properties. In this research work a novel mechanical testing approach has been devised. The mechanical and metallurgical properties of four manually brazed threaded pipe joints made with the induction brazing technique have been determined, the interrelations between these properties have been characterized, and the effects of joint geometry on the mechanical performance of the braze has been investigated. The quality of the joints was evaluated and some recommendations for their improvement have been made. For the present investigation, one of the most suitable filler metals (Bag24, Ag50-Cu20-Zn28-Ni2) has been applied.

The results from the mechanical testing techniques demonstrate the capability to determine the tensile strength, the soundness of the brazed joint, and the performance of the joint during the expansion process. For the expanded pipe joints, depending on the position where the tensile load is applied, a range of ultimate tensile strengths up to 560 MPa are achievable.

Results from optical microscopy, scanning electron microscopy, and energy dispersive x-ray analysis (SEM/EDX) showed that the structure of the braze comprises a (Ag-Cu) eutectic, a (Ag-Cu-Zn-Ni) solid solution and a silver matrix. It was also concluded that the filler Bag24 has a good wettability on the steel surface, which makes it possible to provide appropriate bonding properties (good interface with no cracks or defects) with the steel surface during brazing.
1. Introduction

1.1. Industrial relevance

The main challenges facing operators in the oil & gas industry are accessing new reservoirs that currently cannot be reached economically, and keeping profitable production from older fields. Expandable tubular solutions are expected to play a key role in meeting these challenges. The technology concept, in its simplest form, involves cold working pipes underground. Using a mandrel or pig, a pipe is mechanically deformed beyond its elastic limit, see figure 1. The diameter of a solid tubular is expanded and as a result can provide cost effective solutions to several tubular problems that are currently considered as obstacles to comprehensive reservoir exploitation. With this technology, operators can use smaller holes to drill deeper wells or to extend the reach of deviated wells to access untapped reservoirs [1]. Other potential benefits include preventing or postponing premature well abandonment, minimizing internal diameter loss during casing repair, imposing cost-efficiency in multi-well remediation programs, increasing production in mature fields and affording savings in drilling fluids and associated equipment, since smaller hole sizes may be drilled. A comparison between a conventional well and a well that uses expandable tubulars is shown in figure 2. Using expandable tubulars it is possible to design and create wellbores that begin with a 14 inch (35.6 cm) casing, whereas a conventional wellbore begins with a 26 inch (66 cm) casing [1].

Figure 1. Expansion process.
Figure 2. Comparison of a conventional well diagram versus well diagrams that use expandable tubulars. Well designs have the same production capacity [1].

1.2. Existing problems

Some of the main challenges that need to be addressed include: determination of a suitable material that can be expanded, designing the expansion process and equipments, choosing an appropriate joining technique, and development of reliable testing techniques and analyzing procedures.

Pipe is supplied in 10 m length and these must be joined to form a continuous tube. The subsequent expansion can be detrimental to conventional threaded connections, see figure 3. The joints are expected to provide sealability and strength for the required application, which is usually in a pressurized condition. Brazing as a metallurgical joining technique is a potential solution for this problem. Application of threaded joints which have been brazed can provide the joint with the strength required to tolerate the expansion process and the sealing characteristics required to maintain reliability for the required operation. Choosing a suitable brazing technique and a filler metal to produce sound joints is a significant challenge. Joints should be mechanically and metallurgically designed to meet the required criteria for dynamic and static loads in the corrosive and pressurized well environment. For the specific geometries that are used, a
wide variety of brazing techniques and filler metals are available, and joint properties are influenced by a number of environmental and processing variables. It is therefore necessary to develop a reliable testing strategy to determine which combination of variables will produce acceptable results.

![Diagram of a typical gas-tight threaded connection with labels for Sealing Area, External wall, Pin, Threads, Internal wall, and Box.]

**Figure 3.** A typical gas-tight threaded connection.

### 1.3. Research objective

The objective of this research is:

To characterize the brazed joints made on threaded connections of steel pipe X52.

This includes:

- Development of a suitable mechanical testing approach to determine the mechanical properties of the threaded brazed joints.
- Determination of mechanical and metallurgical properties of the brazed joints made under specific conditions.
- Characterization of the interrelations between these properties.
- Investigation of the effects of the joint geometry and an expansion process on mechanical and metallurgical properties of the braze.

### 1.4. Research approach

Based on the objectives in section 1.3, it is necessary to devise suitable mechanical testing techniques to cope with geometry of the threaded joint. A new tensile test has
been devised to generate information about the tensile strength of the brazed joint. A bending test is used to evaluate the soundness of the joint and its capability to tolerate the tensile load exerted upon it during the expansion process. Optical microscopy is used to generally evaluate the cross sectional surfaces of the joints and to determine the state of interfaces, phases that are present, and morphological characteristics of microstructures that develop during the brazing operation. Scanning electron microscopy and energy dispersive x-ray analysis (SEM/EDX) are used to characterize the diffusion processes that occur due to brazing and applied thermal cycles, the distribution of alloying elements, and the bonding state of the joints in more detail. Micro-hardness testing is applied on cross-sections of the joint to generate information about variation of hardness across the joint and to provide an indication of the ductility of the phases present in the joint.

1.5. Thesis outline

This thesis is subdivided into six chapters. Following this introduction, chapter 2 provides a description of the state of the art on brazing techniques, important parameters in brazing, and silver-copper-zinc filler metals. Particular attention is paid to the mechanisms of brazing of steels and silver-based filler metals that have been used to make brazed joints involving steel to steel or steel to other materials. In chapter 3, the designs for new test specimens and a fixture, and the sample preparation for the SEM/EDX and optical microscopy are discussed. In chapter 4, the experimental results of the testing techniques that have been applied are presented and discussed. A more detailed discussion on the brazed joints and the testing procedures is presented in chapter 5. Finally, the general conclusions from the research are presented in chapter 6. Figures, tables, and references are numbered sequentially throughout this work and the list of references may be found on pages 125 to 130 following the conclusions.
2. Literature Review

2.1. Joining of Materials

Joints are often the weakest part of an assembly and usually are located at the most highly stressed points. Careful attention to the joining processes can result in great rewards in economy and reliability of products. There are a large number of joining processes, and one of the problems manufacturing engineer faces is deciding which technique will produce acceptable results at the lowest cost. There are no simple answers. A change in material, size of the product, or the geometry can influence the choice of joining technique. On small lots of complex parts, fastening is often the best choice, whereas on long production runs, welds are often preferred because they are stronger and less expensive [2]. Ideally, a joint should not be distinguishable from the material surrounding it. Some processes, such as diffusion bonding, come very close to this ideal; however, most are either expensive or limited to a few materials.

Apart from mechanical fasteners, all joining processes, including adhesive bonding, soldering, brazing, and welding, involves the formation of a bond between parts. Generally, any two surfaces can be bonded to each other if they be brought into intimate contact. Unfortunately, two factors inhibit this contact [2]; the first is surface contamination. Any fresh surface exposed to the atmosphere will adsorb oxygen, water vapor, carbon dioxide, and hydrocarbons very rapidly. Assuming that each molecule that hits the surface will be adsorbed, the pressure time product to produce a monolayer is $10^8$ atm.s [2]. So at pressure of 1 atm the required time for formation of a monolayer of contamination is around 10 ns. The second reason that surfaces will not bond when placed in contact is that the solid surfaces do not mate perfectly. On an atomic scale the smoothest surface contains numerous peaks and valleys; hence the true contact area is usually less than 10% and rarely more than 30 % of the apparent contact area [2]. The contamination and the partial contact area can be considered as chemical and geometric barriers to bonding, respectively. Any successful bonding process must overcome both of these problems.

Brazing is a useful technique for the metal fabrication engineer. One of the main advantages of this production method is its versatility and the availability of a large variety of brazing materials and techniques. Brazing is a thermal joining process which
is characterized by its temperature, which has to be lower than the solidification temperatures of the base materials to be joined, and equal to or higher than the melting temperature of the filler material. As the filler is partly or totally molten, interactions such as diffusion and alloying can occur between the filler and base metals. One major advantage in comparison to conventional welding techniques is the possibility to join materials with very different chemical compositions, such as steel and copper or steel to ceramics. In general, the same brazing alloy can be used for a variety of base materials [3]. Copper and its alloys have been reported to be common filler metals for brazing of steels in some references [4-15].

2.2. Brazing processes

Brazing processes are usually designated according to the source or technique of heating. Torch brazing, induction brazing, furnace brazing, dip brazing, resistance brazing, diffusion brazing, electron beam brazing, exothermic brazing, infrared brazing, laser beam brazing and microwave brazing, are the most common techniques. Some of these techniques are capable of producing a joint in short time intervals. These processes include induction brazing, infrared brazing, electron and laser beam brazing, and microwave brazing. For the purposes of this study, attention will be focused on induction brazing.

2.2.1. Induction Brazing

Electromagnetic induction, simply induction, is a heating technique for electrical conductive materials. Induction heating is frequently used in thermal processes such as the melting and the heating of metals. It has the important characteristic that the heat is generated in the material itself. As a result, induction has a number of intrinsic advantages, such as a very quick response and a good efficiency. The process also allows heating very locally.

The principle of induction brazing is mainly based on two well-known physical phenomena, electromagnetic induction and joule effect [17]:
Electromagnetic induction

If a loop of conductive material is placed in an alternating magnetic field an alternating current will be induced inside the loop, see figure 4a. The relation is as follows:

\[ \mathcal{E} = \frac{d\Phi}{dt}, \]  

in which \( \mathcal{E} \), \( \Phi \), and \( t \) are induced voltage, magnetic flux, and time respectively. When the loop is short-circuited voltage will be produced that opposes the alternating magnetic field, described by the Faraday–Lenz law, see figure 4b.

![Diagram of electromagnetic induction](image)

**Figure 4.** (a), (b) Induction law of Faraday, (c) induction of eddy currents.

If instead of the short-circuited loop, a solid conductor (e.g. a cylinder) is placed in the alternating magnetic field then eddy currents will be induced, see figure 4c. The eddy currents heat up the conductor according to the Joule effect.
The Joule effect

When a current $I$ flows through a conductor with resistance $R$, the power is dissipated in the conductor according to the following equation:

$$P = RI^2.$$  

(2)

This will produce heat and increase the temperature of the conductor. It should be noted that the resistance should be carefully introduced into the equation, as the distribution of currents is not uniform in the material. Callebaut [17] proposes a simplified relation for generated power:

$$P = \pi d h H^2 \sqrt{\pi \rho \mu_0 \mu_r f}, F.C,$$  

(3)

where $d$ is the diameter of the cylinder, $h$, the height of the cylinder, $H$, the magnetic field intensity, $\rho$, the resistivity, $\mu_0$, the magnetic permeability of a vacuum, $\mu_r$, the relative permeability, $f$, the frequency, $C$, a coupling factor, and $F$ is a power transmission factor.

Alternating currents concentrate on the outside surface of materials. This is called the skin effect. Eddy currents are therefore greater at the surface and diminish with depth into the material. This means that the most of the heat is generated at the outside surface. The skin effect is characterized by its penetration depth $\delta$. The penetration depth is defined as the thickness of the layer, measured from the outside, in which $1/e^2$ (~87%) of the power is developed [17]. The penetration depth can be calculated from Maxwell’s equations. For a cylindrical load with a diameter that is much bigger than $\delta$,

$$\delta = \frac{\rho}{\sqrt{\pi \mu f}},$$  

(4)

where $\rho$, $\mu$, $f$ are resistivity, magnetic permeability, and frequency respectively. The penetration depth, on the one hand, depends on the characteristics of the material to be heated ($\rho$, $\mu$) and on the other hand, is influenced by the frequency. The frequency dependence offers a possibility to control the penetration depth and therefore heating cycle. High frequency sources produce superficial heating. Frequencies for induction brazing generally vary from 5 kHz to 500 kHz [18].
Applications

In this brazing technique the brazing filler metal is preplaced inside the joint. Careful design of the joint and the induction coil is required to make sure that uniform heating will occur at the same time and at every part of the joint [18,19]. The presence of fluxes is also required except in the case that a protective atmosphere is being used as a replacement. Rapid heating, the possibility to reach very high temperatures, suitability for automation, the possibility for accurate determination of the heated area, and clean operating conditions are the main parameters which justify usage of this heating technique for a variety of brazing applications.

As a disadvantage, it is important to note that local overheating is likely to occur if the shape of the parts is such that a coil cannot follow the surface contours. As a result, less efficient heating occurs. Slower heating allows time for temperature gradients within the parts to be smoothed out [20].

In reference [16] induction assisted laser beam welding of HSLA steel sheets is reported. Several strategies of induction were tested and compared to each other with regard to the applied temperature fields. The welding results were evaluated with respect to the metallurgical reactions and the resulting mechanical seam properties. For the materials investigated, a significant hardness reduction without the loss of seam strength was achieved.

Other brazing methods such as infrared, microwave, electron and laser beam brazing, are discussed in references [21, 22, and 23].

2.3. Fluid Behavior during Brazing

2.3.1. Wetting

Wetting is a substance’s ability to spread and as a result become intimate with a surface. Wettability depends on the relative magnitude of two variables: the adhesion between liquid and the surface, which is due to the attraction between molecules of the liquid and molecules of the solid, and the cohesion of the liquid, due to intermolecular affinity. A measure of how well a liquid wets a solid is the contact angle \( \theta \). Figure 5 shows drops of liquid that have come to rest on a surface. The angles \( \theta \) formed between
the surfaces and the lines tangents to the drops determine how well the wetting has taken place. The lower the contact angle, the better the wetting. All liquids have a surface tension, measured as the force per unit length on a surface, which opposes expansion of the surface area. Surface tension results from the cohesive forces between adjacent molecules of the liquid [24], and can be visualized with reference to a molecule in a stationary liquid drop. In the body of the liquid the forces acting on the molecule are the same on all sides. At the free surface of the drop, the molecule is not opposed by a corresponding outward force. This means that every molecule on the surface is under a constant force tending to pull it inside the drop. As a result the surface exhibits a tension, and will contract at any opportunity to minimize the surface energy [24]. The lower this surface tension, the better the wettability of the liquid.

![Wetting states of a liquid drop on a solid surface.](image)

**Figure 5.** Wetting states of a liquid drop on a solid surface.

### 2.3.2. Capillary Flow

Capillary flow is the dominant physical principle that ensures good brazement, providing that both faying surfaces to be joined are wetted by the molten filler metal. A capillary is usually thought of as a small tube with a very small inside diameter. When applied to brazing, a capillary is simply two solid surfaces which are close enough together so that capillary attraction can occur [25]. Capillarity is a result of surface tension between base metals, brazing filler metals, flux or atmosphere, and the contact angle between base metal and filler metal. Liquid metals such as molten brazing alloys have high surface tensions, between three and ten times as great as water [25]. If the adhesive attraction of closely placed surfaces for a liquid is greater than the cohesive force between liquid molecules, there will be a good wettability and the imbalance
between these forces will cause the liquid to flow. Flow of filler is affected by dynamic considerations involving fluidity, viscosity, gravity, vapor pressure of the elements, and metallurgical reactions between brazing filler metal and base metal [26]. The distance that a liquid will flow into a capillary space increases as the clearance of the surfaces is reduced [26]. The rate of the flow of the liquid decreases as the clearance is reduced. The wetting characteristics of the brazing filler metal have no effect on the reach or the rate of capillary action, but determine whether capillary action will be generated at all [26]. According to Yoshida [10], the average velocity, \( v \), of capillary flow between parallel, horizontal surfaces, is given by the following expression:

\[
v = \frac{D \gamma \cos \theta}{6 \eta s},
\]

(5)

where \( D \) denotes the joint gap, \( \gamma \) is the surface tension of the brazing alloy, \( \eta \) its viscosity, \( \theta \) contact angle, and \( s \) the distance through which the metal has flowed. In this instance, there is no limit to the distance through which the brazing alloy can flow, but the average velocity of the flow will decrease with increasing distance from the point of feeding; the time required for the brazing alloy to flow over the distance \( s \) is given by:

\[
t = \frac{6 \eta s^2}{D \gamma \cos \theta}.
\]

(6)

Similar relationships have been proposed to apply to vertical or inclined capillaries, but in these instances there is a maximum height, \( H \), to which the molten metal will rise, given by:

\[
H = \frac{2 \gamma \cos \theta}{D \rho g}
\]

(7)

where \( \rho \) is the density of the metal and \( g \) acceleration due to gravity; hence, the maximum joint gap \( D \) at which the column of a molten metal of height \( H \) will be held in the inclined or vertical capillary is given by:

\[
D = \frac{2 \gamma \cos \theta}{\rho g H}.
\]

(8)
Although it would appear that for a given parent metal/brazing alloy combination, $v$, $t$ and $H$ are linear functions of $D$, in practice the effect of $D$ on the flow of the brazing alloy has to be considered in relation to several other factors. The average velocity of the capillary flow increases with increasing surface tension and decreasing viscosity and reduced contact angle. Since all these three characteristics of the brazing alloy change in a favorable direction with rising temperature, it follows that narrower joint gaps can be used when relatively high brazing temperatures are employed [27].

2.4. Brazing Process Parameters

Joint strength and tightness, corrosion susceptibility, fatigue resistance, and temperature stability are some of the concerns which determine the selection of joint design, braze filler materials, and processing parameters. The main parameters that affect the final results of brazing processes are:

- Base metal characteristics
- Surface preparation
- Joint design and clearance
- Filler metal characteristics
- Fluxing methods
- Temperature and time

The influence of these parameters is briefly discussed below.

2.4.1. Base metal characteristics

A high strength base metal produces joints of greater strength than those made with softer base metals. Cold – worked strengthened base metals will be annealed and the joint strength reduced when the brazing temperature and time are in the range of annealing of the base metal being used. Materials in the annealed condition will generally experience no appreciable change due to brazing. The heat treatment considerations of low alloy steels are important factors in determining the specific
brazing fillers and brazing temperature to be used. According to reference [28] all the silver-based brazing filler metals can be used for brazing low-carbon and low-alloy steels. The silver-based filler metals containing nickel usually provide better wettability and are preferred for brazing low – alloy steels where joint strength is most important. The low cost and high strength of copper make it a good candidate for brazing of steels. The high solidus temperature (1095 – 1150 °C) necessary when copper based filler metals are used often allow simultaneous brazing and heat treating of low alloy steels. Silver – copper alloys used to braze iron and steel, often contain zinc and cadmium to lower the solidus and liquidus temperatures. Tin is added in place of zinc or cadmium when constituents with high vapor pressure are objectionable. Other brazing filler metals containing elements such as lithium, phosphorus, or boron, reduce surface oxides on the base metals and form compounds with melting temperatures below the brazing temperature. Such filler metals are essentially self-fluxing [29].

Nickel based filler metals have been used for joining low carbon and low alloy steels when special joint requirements exist. Silver brazed joints cannot be used for high temperature service; the recommended maximum service temperature is 370 °C [38]. Nickel based filler metals provide joints that have good corrosion resistance and high temperature strength. These filler metals alloy with stainless steel, however, and form phases with two undesirable characteristics: the phases are considerably less ductile than either the base metal or the filler metal even at elevated temperatures, and thus are potential source of failure; and the alloys formed have a high melting temperature which increase the possibility that they will freeze and block further flow into the joint during brazing [30].

2.4.2. Surface preparation

All metals are covered by oxide films, which form when a metal is exposed to an environment containing oxygen. Oxides can be removed mechanically or chemically, but immediately a new oxide layer will start to form. The thickness and tenacity of the oxide layer depends upon the metal and the environmental conditions. Oxides are barriers to wetting because their atoms are bonded ionically. A characteristic of ionic bonding is that there are not any free (or easily detachable) electrons, which are a prerequisite for forming metallic bonds. Thus, all oxides must be removed if wetting is
to take place [24]. Apart from cleanliness and freedom from oxides, surface roughness is important in determining the ease and evenness of flow of the brazing filler metal. Generally a liquid which wets a smooth surface will wet a rough one even more. A rough surface will modify filler metal flow from laminar to turbulent, prolonging flow time and increasing the possibility of alloying and other interactions [31].

Base material surface finish can be influenced in pre-braze processing and should be considered when designing the brazement and selecting the braze process [32].

2.4.3. Joint design and clearance

Brazement design is a critically important characteristic of a brazed joint structure. The design is responsible for reliability and proper service behavior of brazed products [33]. The required strength and corrosion resistance, the necessary electrical and thermal conductivity, the materials to be joined, the mode of application of brazing filler metal and the post-joining inspection needs are important factors that influence joint design. Joint design should take account of preplacing of the brazing filler metal if required and this entails care in setting the dimensions of preformed filler metal rings and other special shapes [34].

The smaller the clearance the easier it will be for capillarity to distribute the brazing filler metal throughout the joint area and the less the likelihood that voids or shrinkage cavities will form as the brazing filler metal solidifies. Joint strength increases as joint gap decreases, see figure 6. This figure demonstrates the variation of tensile strength with joint clearance for butt joints of stainless steel brazed with brazing filler metal AWS Bag-1a. These data show that at small joint clearances—i.e., those below 0.15 mm (0.006 in), joint tensile strength is quite high and even approaches that of the stainless steel [35]. According to some experts, the ideal clearance for production work is 0.05 – 0.13 mm. Joint clearances up to 0.13 – 0.20 mm are also acceptable when silver based filler metals are used [36]. As the joint becomes thinner, the brazed metal is constrained, preventing it from deforming due to the adjacent base metal. This produces a triaxial state of stress in the brazement, which makes the entire joint stronger. This phenomenon is termed contact strengthening. The contribution of triaxiality to joint strengthening has been investigated by West et al. [37]. In theory, contact strengthening will continue to increase as the joint becomes thinner. For example, thin silver-activated diffusion
bonded steel joints have produced failure stress which are five times the strength of the bulk silver; however, in brazing the strength usually peaks at an optimum joint thickness and decreases in thinner joints. This is due to the formation of defects such as porosity or entrapped flux in the thinnest joints.

The optimum joint thickness varies for each braze alloy and must be developed empirically whenever maximum braze strength is required. When dissimilar materials are bonded, thicker joints sometimes act to relieve the differential thermal contraction upon cooling, thus shifting the optimum joint thickness to higher values [2]. Optimum joint clearance should be chosen to lie within the gap – filling range of the brazing filler metal. Joint length, brazing temperature, wide melting range metals, and base metal reactions are other factors that influence optimum joint gap. Joint strength is related to test specimen design and testing method. Thus tests must be conducted in accordance with the proposed production joint design and brazing procedures to obtain specific design strength data. Variations in brazing procedures and joint design will alter the effect of joint clearance on the strength of the joint. The strength of the joint is determined largely by the tensile strength of the filler metal and size of the overlap, if the brazing metal is free from defects. Generally maximum joint strength is developed when the overlap is four times the thickness of the thinnest components of the joint, but this varies according to the base metal [38].
Figure 6. Variation of tensile strength with joint clearance for butt joints of stainless steel brazed with brazing filler metal AWS Bag-1a [35].

Longer overlaps waste preparation time and filler metal, and don’t increase joint strength. According to Schwarts [39] for an exact determination of a length of a lap for maximum strength in flat structures equation (9) can be used, see figure 7:

![Figure 7. Flat lap joint [25].](image)

\[
L = F(T \times \frac{t}{S}) ,
\]

(9)

where L is length of lap, T is tensile strength of the thinner member, F is factor of safety, t is wall thickness of the thinner member, S is the shear strength of the filler metal, and D is the diameter of the inner tube. Strength is the only reason that most of the brazing joints are of lap design. A lap joint can be readily designed to be self-jigging or, as in the case of tubulars, self-aligning. Also preplaced filler metals can be better
held in position in these joints. However, there are some disadvantages as well. They can interfere with fit and function in some applications, they result in increased metal thickness at the joint, and they create stress concentration at the edges of the lap where there is an abrupt change in cross section. These problems can be addressed by intelligent changes in sections to make a smooth path for stress transformation through the joint. Scarf joints offer one such design solution. According to Schwartz [36] and Emilian [41] effects of joint clearance on mechanical performance of the joint include:

- Restraint to plastic flow of the filler metal if the base metal is strong enough
- Possibility of slag entrapment
- Possibility of void formation
- Effect on capillary forces and distribution of filler metal
- Range of interaction between filler and base metal

And effective parameters that determine the required clearance are [40]:

- Types of fluxes (dependence on how well the molten filler can flow through the joint under the effect of the flux)
- Surface finish (very smooth or very rough surfaces will not produce an acceptable bonding, an optimization is required)
- Base metal (dependence on types of oxides that form on the surface and the degree of difficulty for removing them)
- Base metal / filler metal interaction (this may cause changes of composition and solidification in an unexpected temperature range)
- Filler metal (dependent on how extended solidification temperature range is, the smaller the better)
- Joint length and configuration (longer joints require more brazing time and more fluidity of the fillers)
- Thermal expansion of the metals that are involved in the joint (this item will determine the final stress state of the filler and the joint)
2.4.4. Filler metal characteristics and application techniques

A filler metal must satisfy several conditions, some having to do with physical behavior such as its solidus and liquidus temperatures, and some having to do with chemical interaction with the base metals. One way that several of these qualities become important is by their effect on the capillary flow that enables the filler metal to penetrate the joint. It is important to be sure that the brazing temperature is 10-40°C above the liquidus of the filler metal [29]. If not, some constituents of the brazing alloy may not be melted entirely. This can affect the strength of the joint, in addition to making it more difficult to achieve good penetration (since the viscosity of the not-fully-molten filler metal is high). The physical properties of the brazing filler metal that determine solubility, erosion susceptibility, strength, corrosion resistance, etc., are inherent chemical characteristics, which are not affected by melting practice [42]. Filler metals must meet the following criteria [3] and [29]:

- Form brazed joints with mechanical properties, suitable for the applied service
- Melt at a lower temperature than the base material (by at least 50 – 100°C)
- Chemical, mechanical, and physical compatibility with base metals being joined
- Sufficient fluidity at brazing temperature to flow through the joint by capillary action
- Homogeneous composition and sufficient stability to minimize separation of constituents during brazing
- Wet surfaces of base metals and form a strong bond
- Ability to produce or avoid interaction with base metals, depending on requirements
- Freedcm from excessively volatile or noxious constituents
- Alloy with the surface of the base metals without dilution, undesirable diffusion, base metal erosion, and formation of brittle phases
- The filler must be chosen such that desired treatment states, as a result for example of hardening, homogenizing and cold-strengthening, are affected as little as possible by the heating.
In addition to simple hand application there are other techniques that can be applied for filler feeding in brazing operation. Thermal spray processes (TS), are capable of coating defined surface areas of components with functional coatings to improve corrosion, erosion, and mechanical properties. Generally all conventional TS processes are characterized by an energy source that melts or warms up a feedstock material and accelerates the spray particles onto a substrate surface, on which the coating forms. The substrate is not molten during the deposition process. Conventional energy sources of TS processes are flame, electrical arc, and plasma. Depending on specific process characteristics the feedstock can be in wire, rod, or powder form. During the time of interaction between particles and gas flow thermal and kinetic energy is transferred to the particles. Particle temperature and velocity at impact on the substrate determine the deposition characteristics and thereby coating properties like homogeneity, density, porosity, bond strength, etc. In high velocity (HV) spray processes, more kinetic and less thermal energy is transferred to the spray particles and as a result the thermal load of the spray particles decreases, which results in less reaction with the spraying atmosphere and low porosity [43].

Cold gas spraying (CGS) is a broader case of thermal spraying and a consequent development of HV TS processes. The spray particle temperature is far below the solidification temperature and velocities can reach 1200 m/s. CGS works by expansion process at high pressure through a convergent/divergent nozzle with spray particle injection in front of the smallest cross section. Heating of the process gas (T< 800 °C) results in increased particle velocities. Though the physical effects of the deposition process are not fully understood, it is known that the particles need to impinge on the substrate with a velocity exceeding a material specific velocity to avoid abrasion and achieve adhesion. CGS can only be applied for materials with high ductility [43]. In comparison to most other TS processes CGS permits manufacturing of coatings with very low porosity and oxide content. For coating materials with low thermal conductivity the bond strength can be increased due to small areas of metallurgical interactions due to local melting. Coatings with properties comparable to bulk materials can be produced with high reproducibility. Gas pressure, gas temperature, spray distance, and powder feed rate are the main parameters that can affect the resulting coating quality which can be characterized by optical microscopy, SEM and EDXS analysis [43].
2.4.5. Fluxing methods

Fluxes and special atmospheres are designed to prevent oxide formation or to chemically reduce any oxidation that occurs during initial heating [44]. The primary function of the fluxes is to improve wetting of the base metal with the filler metal. Flux must be able to dissolve any oxide on the surface of the base metal after it has been cleaned and any oxides in the liquid filler metal. As the molten filler metal should displace the flux from the joint at the brazing temperature, the viscosity and surface tension of the flux and interfacial energy between the flux and the surfaces of parts are important. Therefore, recommended fluxes should be used in their proper temperature ranges and on the material for which they are designed. For successful use, a flux must be chemically compatible with all the base metals and filler metals involved in the brazement. It must be active across the entire brazing temperature. According to Schwartz [45] to braze ferrous alloys and nickel alloys, two flux types can be used: silver brazing or high temperature fluxes. Silver brazing fluxes, which are more expensive than high temperature fluxes, may be chosen to minimize distortion and heat input to the work. To be effective, flux must be molten and active before the filler metal melts, and it must remain active until the filler metal flows through the joint and solidifies upon cooling. Therefore the filler metal solidus temperature determines minimum working temperature of the flux, and the filler metal liquidus temperature dictates the maximum brazing temperature that the flux must withstand. Generally, fluxes are selected to be active approximately 30 °C below the solidus temperature and remain active at least 90 °C above the filler metal liquidus temperature [45]. These temperature ranges depend in practice on the brazing process that is being applied. It is important to note that brazing time affects flux performance. Molten flux forms a protective layer that prevents oxidation only for a finite period of time, oxygen will eventually diffuse through the flux to the base materials. Flux should be properly designed and chosen so that it continually removes newly formed oxides until the end of the heating cycle. Fluxes can only dissolve a limited amount of oxides, so the longer the brazing process, the greater the likelihood that the flux will become saturated with oxide, a condition called flux exhaustion. To avoid flux exhaustion over prolonged heating cycles a flux with higher working temperature range should be chosen [45].
The type of fluxing will have an important effect on the joint clearance to be used for accomplishment of a brazement. A mineral flux must melt at a temperature below the melting range of the brazing filler metal, and it must flow into the joint ahead of the filler metal. If the clearance is small the mineral flux may be trapped in the joint and will not be displaced by the molten filler metal. This will cause joint defects. If the clearance is too large, the molten filler metal will flow around the pockets of flux and result in the formation of inclusions [46]. Similar considerations apply to brazing in a reducing atmosphere. When hydrogen is used as the reducing agent, the reaction with the metal oxides can be represented by

\[ \text{H}_2 + \text{MeO} = \text{Me} + \text{H}_2\text{O}, \]  

(10)

where Me denotes the metal. The reaction is reversible, and one of the factors which determine its direction is the relative concentration of H\textsubscript{2}O. All other factors being equal, there is a certain concentration of H\textsubscript{2}O (normally expressed in terms of the dew point of the gas), different for each oxide, above which the oxide will not be reduced. While the gas supplied to a brazing furnace may be sufficiently dry, the water vapor concentration in the immediate vicinity of the metal oxide / gas interface may exceed the critical level unless H\textsubscript{2}O\textsubscript{2}, formed as a result of the reducing reaction, is continuously removed. The longer and narrower the joint gap in an assembly brazed in a reducing atmosphere, the more restricted the flow of the gases, and the more likely it is that the normally “dry” gas will fail to perform its function [27].

The flux which is required for induction brazing should decompose oxides without corroding the base metal or the filler metal and it should be extremely active because of the short brazing period employed. Type FB3A flux (borates and fluorides) is used for an estimated 95% of the induction brazing that involves steel [47].

Fluxes should form non-hygroscopic reaction products [48]. Fluxes are generally required, but fluxless brazing with filler metals free of cadmium and zinc can be done on most metals in an inert or reducing atmosphere such as dry hydrogen, dry argon, vacuum and combusted fuel gas) [49]. Where more than one flux is suitable for an application, safety and cost are the main features governing selection [50]. The selection of flux for brazing low-alloy and carbon steels depends on the brazing filler metal [51].
2.4.6. Temperature and time

For the strength of brazed joints there are several important parameters such as temperature, time, pressure and atmosphere. Thermal mismatch of the components leads to the development of residual stresses during cooling from brazing to room temperature [52]. Temperature has an important effect on the wetting action. The selection of the optimum braze temperature requires an understanding of the influence of temperature on both wetting and flow of the filler metal. Low brazing temperatures are usually preferred to minimize heat input, damage to the base metal, and filler/base metal interactions, and to increase life of fixtures and other tools. High brazing temperature are preferred in order to take advantage of higher melting, but more economical, brazing fillers, to combine annealing, stress relief or heat treatment of the base metal with brazing, and to promote filler metal/base metal interactions that fortify the joint properties. Alloying action between filler metal and parent metal is a function of both temperature and time. Brazing time will depend on the thickness of the parts and amount of fixturing required to position them. The time should be restricted to that necessary for the filler metal to flow through the joint and avoid excessive interaction between filler and the base metal. Normally one or two minutes at the brazing temperature is sufficient to make the joint. A longer time at the brazing temperature will be required where the filler metal remelt temperature is to be increased and when diffusion will improve joint strength and ductility [53].

Roulin et al. [54], discuss the effects of heating cycles for a furnace-brazed system of aluminum and stainless steel; the results show that very high strength joints can be produced when short (1-2 min) brazing times are used. When longer heating cycles (>30min) are encountered, such as those in furnace brazing, relatively brittle joints may be formed. In extreme cases, the joints can become so fragile that spontaneous fracture occurs during handling of brazed parts. An obvious explanation for such brittle behavior is the formation of intermetallic layers. Such correlation between intermetallic growth and reduced braze strength has been established for many brazed material systems. The results of the study concluded that the brittle fracture is associated with the formation of a specific layer of continuous intermetallic, which can be avoided within a reasonable processing – time window. Microstructural examination of the interface revealed the formation of two distinct layers of intermetallic compounds along the interface between
the aluminum and stainless steel. Micro-hardness indentation shows that both layers feature very high hardness (above 600 HV); therefore, they have the potential for embrittling the joint. Besides these intermetallic layers, pores and entrapped flux were found at various locations and in variable quantities along the interface; these were also visible on fracture surfaces and frequently contained crystallized fluxing compounds. This could indicate that either the amount of filler metal was insufficient or, alternatively, that the joint clearance was too wide. The shear strength as a function of holding time was drawn and it featured scattered results that can be ascribed to voids and entrapped flux along the brazement [54].

The uniform distribution of heat and protection of the joint from any hot spots is crucial. Failing to consider this important issue can result in melting of the base metal and dilution with the filler metal that may increase its liquidus temperature and make the flow more sluggishly. In addition, the flux may be overheated and thus loose its ability to promote capillary flow, and low melting constituents of the filler metal may evaporate. The rapid heating rates are a major advantage when brazing filler metals that tend to vaporize or segregate are used [55].

In another research by Liu-Ho Chiu et al. [73], WC-Co and SAE1045 carbon steel have been joined by vacuum brazing to investigate the joint property and microstructure. The influence of the filler metal, brazing temperature and bonding time on the joint shear strength was examined. The shear strength of WC-Co/Cu/SAE1045 joints brazed at various temperatures and bonding time is shown in figure 8a. The shear strength of joint brazed at 1100°C/5 min was 245 MPa and, at temperature of 1140°C/15 min, the shear strength rose 32 % to 324 MPa. As shown in the figure, shear strength was mainly affected by the elevation of brazing temperatures from 1100 to 1140°C and was directly related to the formation of bonding interface microstructure, i.e., the growth of the precipitation layer on the WC-Co interface. This occurs due to the increase of brazing temperature and bonding time. When brazing temperature reached 1140°C, the columnar precipitation layer interconnected the WC-Co/Cu/SAE1045 brazed joint, resulting in the maximum shear strength. Figure 8b shows the shear strength of WC-Co/C52100/SAE1045 brazed joints at various temperatures and bonding time [73].

The shear strength of joint brazed at 1080°C/5 min was 340±10 MPa and slightly increased to 358±10 MPa with 15 min bonding time. The shear strength at brazing
temperature of 1120°C was slightly lower than that at 1080°C. Overall, the shear strength of WC-Co/C52100/SAE1045 brazed joints was better than WC-Co/Cu/SAE1045 brazed joints at the same bonding temperature. Prolonging bonding time promotes the combination of the WC-Co, SAE1045 and melted filler alloy at the interface. The bonding area of the precipitation layer on the SAE1045 end expanded with increasing bonding time, so as to improve the shear strength of the brazed joint. From the micrographs of WC-Co/Cu/SAE1045 brazed joints, a Fe-Co-Cu interlayer was observed at the interface of WC-Co and Cu. With increasing temperature and bonding time, the layer thickness increased. At a brazing temperature of 1120°C, the precipitation layer grew and eventually connected both substrates. The shear strength of WC-Co/Cu/SAE1045 brazed joints increased with increasing precipitation layer thickness [73, 74].

![Graph showing shear strength vs brazing temperature and time](image)

**Figure 8.** Shear strength of (a) WC-Co/Cu/SAE1045 and (b) WC-Co/C52100/SAE1045 Joints brazed at various temperatures and bonding time [73].

### 2.5. Silver-Copper-Zinc Filler Metals

For silver-copper-zinc filler metals fluxes are generally required, but fluxless brazing with filler metals free of cadmium and zinc can be performed on most metals in an inert or reducing atmosphere, such as dry hydrogen, dry argon, and vacuum. When brazing of steels the wettability of silver- copper brazing filler metals decreases as the silver content increases. Addition of cadmium to silver-copper-zinc brazing filler metals dramatically lowers their melting and flow temperatures. It also increases the fluidity and wetting action of the filler metal on a variety of base metals. Cadmium bearing filler
metals should be used with caution. If they are improperly used and subject to overheating, cadmium oxide fumes can be generated which are a health hazard; excessive inhalation of these fumes must be avoided [57-60]. As these filler metals are not intended for fluxless brazing, an appropriate flux should always be used when brazing in air. Zinc is commonly used to lower the melting and flow temperature of silver – copper brazing filler metals. Zinc is by far the most helpful wetting agent for joining alloys based on iron [62]. Alone or in combination with cadmium or tin, zinc produces alloys that wet the iron group metals but do not alloy with them to any appreciable depth. The high cost of silver and the toxicity of cadmium fumes necessitate finding a replacement for these fillers. Some studies [63] determined the suitability of Cu/15-40Sn/5-15Mn filler metals as replacement. The working temperatures of these fillers are slightly higher than silver based filler metals, but this has to be weighed against the economics and the toxicity of cadmium containing fillers [63]. Generally, as the combined zinc and cadmium content is increased beyond 40%, the ductility of the filler metal decreases. This puts a practical limit on how much the flow temperature of silver based filler metals can be lowered.

Ag-Cu-Zn filler metals and their microstructural properties in joints between steel and TiC cermet, have been characterized by Zhang et al. [66]. According to this work, utilization of the Ag–base alloy with Zn can improve the wetting and spreading on the TiC cermet, and the disadvantageous effects of Zn on corrosion resistance of the joint can be reduced by the evaporation of Zn after the alloy melts in a vacuum furnace. In SEM pictures obtained from sections made on the joint, a lot of TiC particles diffused from TiC cermet into braze zone, which indicates that Ag–31Cu–23Zn has good wetting capability on TiC cermet, see figure 9. When the contents of Cu and Zn increase in the brazing alloy, a lot of Cu aggregates in zones A and C, and a little Cu exists in zone B to form few black blocks. The thin reaction layer near the Ag–Cu–Zn/steel interface is composed of (Fe, Ni) solid solution and (Cu, Ni) solid solution. The whole brazing process can be divided into two steps. Firstly, when the brazing temperature is up to the melting point of the Ag–Cu–Zn brazing alloy, it melts and becomes liquid. At the same time, a little Ni and TiC particles in the TiC cermet and a little Fe in the steel diffuse into the brazing alloy. In the brazing alloy, a lot of Cu diffuses to the interface of the brazing alloy/matrix, and Ag is left in the middle of the brazing alloy. In addition a little Ni and Ag dissolve in the Cu of zones A and C, and the black stripes and blocks of
zone B, which is Cu solid solution. In the same manner, there is a little Cu dissolved in the Ag of the white phase in zone B, Ag solid solution occurs during the brazing. Both Ni and Fe diffused from the matrix and form (Fe, Ni) solid solution in zone D. Meanwhile, there is a little Ni dissolved in Cu diffused from brazing alloy to form (Cu, Ni) solid solution in zone D. Thus, the reaction products of the joint brazed with Ag–31Cu–23Zn are respectively Cu solid solution, Cu solid solution (black stripes and blocks) +Ag solid solution (white phases), Cu solid solution, (Fe, Ni) + (Cu, Ni) from TiC cermet to steel side. The thin reaction layer near the Ag–Cu–Zn/steel interface is composed of (Fe, Ni) solid solution and (Cu, Ni) solid solution [66].

In another study by Zhang et al. [67], to increase bonding efficiency and minimize the adverse effect of extensive reaction during vacuum brazing, high frequency induction brazing with Ag-54Cu-33Zn foil was used to bond TiC Cermet to steel. The focus was on the interface microstructure and mechanical properties of the joint. The microstructure of the filler is shown in figure 10.

![Diagram](image)

**Figure 9.** (a) The microstructures of TiC cermet/Ag–31Cu–23Zn/steel interface, (b) TiC cermet/Ag–Cu–Zn interface, (c) Ag–Cu–Zn/steel interface (1123 K, 20 min) [66].
In this figure zone A is Cu based solid solution, B is a Ag based solid solution + Ag-Zn compound. The microstructure was observed by means of electron probe X-ray microanalysis. The elemental concentration was examined by energy dispersive X-ray spectroscopy (EDS) and the reaction products were determined by X-ray diffraction (XRD). The room temperature shear strength was evaluated with a mechanical testing machine [67].

Based on EDXS results, the presence of Ni$_2$ZnC$_{0.7}$ intermetallic compound in zones A, C, D and E has been detected (figure 11). The results from shear tests showed that the maximum shear strength of the joint is 105 MPa when brazed at 1123 K for 60 s, the fracture site of which is located on Cu solid solution+Ni$_2$ZnC$_{0.7}$ layer (I layer) beside TiC cerments and Cu solid solution+ Ni$_2$ZnC$_{0.7}$ +Ag soli solution layer (II layer) in the middle of the brazing alloy. It has been reasoned that because the hardness of Cu solid solution + Ni$_2$ZnC$_{0.7}$ (I layer) is higher than that of Ag solid solution (the major product in layer II) the shear strength of the joint fractured in I layer is higher than that of a joint fractured in II layer [67].
The constitution and properties of Ag-Cu-Zn brazing alloys were studied and the position of the three-phase field between the alpha and the beta phases which exist in the ternary system was established by Lveigert [68]. Metallurgical samples with different composition were prepared. Conventional etching solutions were used, e.g., 10% ammonium persulphate with occasional additions of potassium cyanide, ammonia and hydrogen peroxide. The identification of alpha phase near the copper side was reported to be very easy. Good phase contrast for the beta phase against the primary copper crystallization and the silver rich eutectic could be achieved by the use of ferric chloride and cuprous ammonium chloride solutions. A vertical section through the phase diagram, which was developed, is shown, see figure 12. The section represents the constant composition of Ag at 50%, which is a representative of the filler of interest in the present study, Bag24. Mechanical tests, such as tensile, shear, and hardness tests have been performed on different alloy compositions and the results presented as fields inside the diagrams shown in figure 13. The shear strength is in most cases about one-half of the tensile strength.

**Figure 12.** Vertical section through the Ag-Cu-Zn diagram at 50 wt % Ag [68].
Figure 13. (a) Brinell hardness number of the as-cast alloys (b) tensile strength of the as-cast alloys, [ksi] (c) shear strength of the as-cast alloys, [ksi] unit (d) Elongation of the as-cast alloys [68].

Liu and Feng [69], report on vacuum brazing of a TiAl-based alloy to medium-carbon steel joints were made at 1173 K for 2-40 min using Ag-Cu-Zn filler metal. The phases formed and interface structure or microstructure of the joint were investigated by SEM, EPMA and XRD, and the strength of the joint was determined by shear testing. The base materials used in this study were a forged TiAl-based alloy block and a rolled
medium carbon steel bar, and their chemical compositions were Ti-43Al 1.7Cr-1.7Nb (at. %) and Fe-0.4C-1.0Cr-0.7Mn-0.3Si-0.2Ni (wt. %), respectively. The filler metal was 20-μm-thick foils of Ag-Cu-Zn alloy, and the chemical composition was Ag-34Cu-16Zn in weight percent. Four different phase zones occurred in the brazing seam between the TiAl and the steel, marked by G, H, I and J, respectively in figure 14. Zones G, H and I are in the brazing seam, while Zone J is continuous reaction layer adjacent to the steel, although it is thinner [69].

![Image of brazed joint](image.jpg)

Figure 14. Back-scattered electron image of the TiAl/steel joint brazed with Ag-Cu-Zn alloy at 1173 K for 20 Min [69].

Quantitative EPMA results showed the chemical composition of each phase zone. There is little Zn in all the zones, indicating the purpose for removing Zn from the brazing seam by means of vacuum is attained. The major elements in Zone J are Ti and C, and the stoichiometric proportion of Ti to C was approximately 1:1, so the phase corresponding to Zone J must be TiC. The formation of TiC is attributed to the reaction of C diffusing from the steel with Ti diffusing from the TiAl-based alloy and passing through the Ag-Cu-Zn filler metal. The major elements in Zone H are Ag and Cu, and the amount of Ag is much higher than that of Cu, thus the phase corresponding to Zone H is a Ag-base solid solution. The major elements in Zone I are also Ag and Cu, and the proportion of Ag to Cu is similar to the composition of Ag-Cu eutectic, and the
morphology of Zone I is typical of eutectics. Zone G is mainly composed of Cu, Ti and Al, and the contents of Cu, Ti and Al in this zone have a 2:1:2 proportion, so Zone G is composed of Cu-Ti-Al ternary phase, i.e. Ti(Cu,Al)$_2$. The formation of Ti(Cu,Al)$_2$ is attributed to the reaction of Cu in the Ag-Cu-Zn filler metal with Ti and Al diffusing from the TiAl-based alloy. These results show that the four different phase zones in the TiAl/steel joint brazed with the Ag-Cu-Zn alloy correspond to Ti (Cu,Al)$_2$, Ag solid solution, Ag-Cu eutectic and TiC, respectively. It should be noted that Ti (Cu,Al)$_2$, Ag solid solution and Ag-Cu eutectic are all fine and fully mixed, while TiC is only one continuous reaction layer [69].

In another part of the work, the effect of time as an important parameter for determining the shear strength of the joint has been considered. Figure 15 shows the room-temperature shear strength of the TiAl/steel joints brazed at 1173 K for different times. When the brazing time is in the range of 2-20 min, the strength increases with the brazing time, and the maximum strength is 190 MPa. When brazing time is more than 20 min, the strength gradually decreases as the brazing time increases. The change in shear strength with the brazing time is related to the change in microstructure of the joint. When the brazing time is short, e.g. 2 min, the TiC zone does not exist or it is too thin to be seen in the TiAl/steel joint, and Ti(Cu,Al)$_2$ and Ag-Cu eutectic gather on the both sides of brazing seam, respectively, figure 16. When the brazing time is about 20 min, the TiC zone is thin, and Ti(Cu,Al)$_2$, Ag solid solution and Ag-Cu eutectic are completely mixed in the brazing seam (see figure 14), thus the highest strength is attained. When the brazing time is longer, the increase in thickness of the TiC zone results in a decrease of the strength [69].
2.6. Silver-Copper-Sn Filler Metals

Another filler metal group that has been successfully applied for the joining of steel components is the Ag-Cu-Sn group. In terms of their moderate liquidus temperature (725-825°C) and their low Ag contents (15 – 25 %), they are especially attractive for brazing mild steel to mild steel or copper. However, formation of the δ phase in their microstructure, as a result of the high Sn content is considered a barrier for their usage. δ phase is a brittle and hard intermetallic compound, stable to room temperature, which
greatly reduces alloy ductility. Therefore, it is of interest to use alloys with lower Sn content and higher copper as alloying elements. Unfortunately the wettability of these alloys is poor and as a result, joint defects, namely un brazed areas in the joint, make the tensile strength of the joints unpredictable. Thus, it is necessary to improve the wettability of this system [65]. According to He et al. [65], Mn and Ni are useful alloying elements that can be used for this purpose. It has been shown that additions of 1-3% Mn depressed the solidus and liquidus temperatures of this alloys significantly, whereas additions of 1-3% Ni raised the solidus and liquidus temperatures slightly. The hardness of the alloys increased gradually as the concentration of Mn increased from 1-3 %. By contrast, the hardness of the alloy decreased dramatically with the addition of 1-3% Ni. Further investigation with SEM and EDX revealed that the amount of Cu-Sn intermetallic compounds in the microstructure of these alloys increased with the increase in Mn content and decreased with the increase in Ni content. EDX results showed that the solubility of Sn in α-Cu increased when adding 1% -3% Ni to a Cu-Ag-Sn composition, which caused a decrease in the amount of Cu-Sn intermetallic compounds. The addition of Mn and Ni to the brazing alloys improved the stability of joint strength [65]. The fracture surfaces of these joints were examined. No, unbrazed areas were found while brazing with Cu-15Ag-22Sn-3Mn or Cu-15Ag-22Sn-3Ni, which accounts for the stable strength of these joints. The addition of Ni to the brazing alloy was found to increase the tensile strength of the brazed joint more than the addition of Mn, owing to the decrease in the amount of Cu-Sn intermetallic compound in joints brazed with the Ni-bearing brazing alloy [65].

Chatterjee and Mingxi [56] initiated a development study of tin –containing filler metals to replace the silver-based metals containing Cadmium. Tin additions improve the wetting characteristics of ferrous alloys over that obtained with binary Ag-Cu filler metals [58, 59]. Tin containing fillers have applications in brazing jewelry, cutlery, hollowware, etc [61]. Tin is used in silver based filler metals in place of zinc or cadmium when volatile constituents must be avoided. Tin additions to silver- copper filler metals result in a wide melting range. Filler metals containing zinc wet ferrous metals more effectively than those containing tin, and where zinc is tolerable, it is preferred over tin. Tin can maintain a low working temperature range. A typical filler metal contains 60Ag-30Cu-10Sn. It can be used in fluxless controlled atmosphere brazing and vacuum brazing of ferrous and non ferrous alloys. It has a wide working
temperature range (600 to 720 °C). Tin additions improve the wetting characteristics of ferrous alloys over that obtained with binary Ag–Cu filler metals. The most effective composition in the range contains 55Ag–21Cu–22Zn–2Sn. This filler metal has a working temperature of 630 to 660 °C [63]. Another silver brazing alloy without cadmium with extreme low operating temperature and high mechanical properties is 40Ag–30Cu–28Zn–2Sn. Due to the addition of Sn this alloy will show a bright looking joint and more capillary flow than the standard silver brazing alloys. Physical properties of this filler are shown in table 1.

<table>
<thead>
<tr>
<th>Melting Range</th>
<th>Operating Temperature</th>
<th>Strength N/mm²</th>
<th>Weight g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 – 710 °C</td>
<td>690 °C</td>
<td>400</td>
<td>9.1</td>
</tr>
</tbody>
</table>

The effect of tin on melting temperature and microstructure of Ag–Cu–Zn–Sn filler metals have been investigated by Sun et al. [76] for the contents shown in table 2.

<table>
<thead>
<tr>
<th>Chemical Compositions, wt-%</th>
<th>T₁</th>
<th>T₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag 22 Cu 15 Zn 15 Sn 2</td>
<td>612.1</td>
<td>704.8</td>
</tr>
<tr>
<td>Bal. 22 Cu 15 Zn 5 Sn 2</td>
<td>609.6</td>
<td>678.8</td>
</tr>
<tr>
<td>Bal. 22 Cu 15 Zn 8 Sn 2</td>
<td>606.2</td>
<td>657.0</td>
</tr>
<tr>
<td>Bal. 22 Cu 18 Zn 2 Sn 2</td>
<td>613.1</td>
<td>690.4</td>
</tr>
<tr>
<td>Bal. 22 Cu 18 Zn 5 Sn 2</td>
<td>603.5</td>
<td>650.0</td>
</tr>
<tr>
<td>Bal. 22 Cu 18 Zn 8 Sn 2</td>
<td>590.0</td>
<td>635.3</td>
</tr>
</tbody>
</table>

The microstructure of Ag–22Cu–18Zn–2Sn filler metal changes greatly compared with that of the Ag–22Cu–15Zn–2Sn filler metal (figures 17a and 18a) [76]. As the tin content of Ag–22Cu–18Zn–2Sn filler metal is increased to 5%, the filler metal mainly consists of dendrite eutectic phases, and a small amount of Cu₄₁Sn₁₁ and Ag₃Sn intermetallic compounds form as in the case of Ag–22Cu–15Zn–2Sn filler metals (figures 17b and c). Further increase of tin content in Ag–22Cu–18Zn–5Sn filler metal does not cause the microstructure of the filler metal to be changed significantly (figures 18b and c). Figures 17 and 18 show that the amounts of eutectic structures increase while those of α-Ag and α-Cu solid solution decrease with increasing zinc and tin.
contents of Ag–22Cu–Zn–Sn filler metals. Because the melting temperatures of α-Ag and α-Cu solid solutions are much higher than that of eutectic structure, the more the quantity of eutectic phases, the lower the melting temperatures of Ag–Cu–Zn–Sn filler metals. Tensile strength of the joints, made by the above-mentioned fillers on stainless steel-TiNi, has been measured and the results reported in table 3. The elongation of the laser brazed joints using Ag–22Cu–15Zn–2Sn and Ag–22Cu–18Zn–2Sn filler metals is higher than that using other filler metals, which could be associated with the softening of TiNi shape memory alloys (SMA) in the heat affected zone owing to the higher brazing heat input [76].

<table>
<thead>
<tr>
<th>Filler metals</th>
<th>Tensile strength (MPa)</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag-22Cu-15Zn-2Sn</td>
<td>315</td>
<td>14.5</td>
</tr>
<tr>
<td>Ag-22Cu-15Zn-5Sn</td>
<td>332</td>
<td>10.4</td>
</tr>
<tr>
<td>Ag-22Cu-15Zn-8Sn</td>
<td>341</td>
<td>7.9</td>
</tr>
<tr>
<td>Ag-22Cu-18Zn-2Sn</td>
<td>324</td>
<td>13.9</td>
</tr>
<tr>
<td>Ag-22Cu-18Zn-5Sn</td>
<td>362</td>
<td>10.1</td>
</tr>
<tr>
<td>Ag-22Cu-18Zn-8Sn</td>
<td>353</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Figure 17. Microstructure of (a) Ag-22Cu-15Zn-2Sn, (b) Ag-22Cu-15Zn-5Sn and (c) Ag-22Cu-15Zn-8Sn filler metals [76].
Figure 18. Microstructure of (a) Ag-22Cu-18Zn-2Sn, (b) Ag-22Cu-18Zn-5Sn and (c) Ag-22Cu-18Zn-8Sn filler metals [76].
2.7. Silver- Copper- Manganese/Nickel/Titanium Filler Metals

The ternary system of Ag-Cu-Mn has been investigated by Kubaschewski [70]. According to this research, no ternary compounds have been observed in the Ag-Cu-Mn system. The crystal structure and lattice parameters of the unary and binary phases of the system are presented in table 4.

<table>
<thead>
<tr>
<th>Phase/temperature range(°C)</th>
<th>Pearson symbol/Space group/</th>
<th>Lattice parameter [pm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>cF4</td>
<td>a- 408.57</td>
</tr>
<tr>
<td>&lt;961</td>
<td>Fm3m</td>
<td>a- 308.0</td>
</tr>
<tr>
<td>δMn</td>
<td>cl2</td>
<td>a- 386.0</td>
</tr>
<tr>
<td>1236-1148</td>
<td>Im3m</td>
<td>a- 308.0</td>
</tr>
<tr>
<td>γMn</td>
<td>cF4</td>
<td>a- 386.0</td>
</tr>
<tr>
<td>1138-1087</td>
<td>Fm3m</td>
<td>a- 361.46</td>
</tr>
<tr>
<td>Cu</td>
<td>cF4</td>
<td>a- 361.46</td>
</tr>
<tr>
<td>&lt;1084</td>
<td>Fm3m</td>
<td>a- 361.46</td>
</tr>
<tr>
<td>βMn</td>
<td>cP20</td>
<td>a- 631.52</td>
</tr>
<tr>
<td>1087-707</td>
<td>P432</td>
<td>a- 631.52</td>
</tr>
<tr>
<td>αMn</td>
<td>cl58</td>
<td>a- 891.23</td>
</tr>
<tr>
<td>&lt;707</td>
<td>43l</td>
<td>a- 891.23</td>
</tr>
<tr>
<td>γ3(Mn-Cu) &lt;700</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>γ2(MnCu3) &lt;450</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>γ3(Mn-Cu) &lt;410</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The ternary system of Ag-Cu-Ni has been evaluated by Kubaschewski [71]. According to the research, no intermediate phases have been reported in the binary systems or in the ternary system. The unary phases are shown in table 5.
Table 5. Crystallographic data of solid phases [71].

<table>
<thead>
<tr>
<th>Phase/temperature range(°C)</th>
<th>Pearson symbol/Space group/Prototype</th>
<th>Lattice parameter [pm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>cF4</td>
<td>a 408.57</td>
</tr>
<tr>
<td>&lt;961</td>
<td>Fm3m Cu</td>
<td></td>
</tr>
<tr>
<td>Ni_{1-x}Cu_x</td>
<td>cF4</td>
<td>a 352.40</td>
</tr>
<tr>
<td>(Ni)</td>
<td>Fm3m Cu</td>
<td>a 361.46</td>
</tr>
<tr>
<td>&lt; 1455</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Cu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 1084.62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An important characteristic of silver based filler metals containing small additions of nickel is improved resistance to corrosive environments [64].

In the work by Elrefaey and Tillmann [72], the lap joint of a commercially pure titanium plate (CP Ti) joint to a low-carbon steel plate was produced in a vacuum-brazing furnace using a silver-based filler alloy at different temperatures and lap widths in order to investigate the effects of brazing parameters on the joint strength and structure. A near-eutectic silver based alloy with a few percent of Ti (Ag-Cu45.5-Ti 3.5, at. %) was selected as the brazing alloy. The results show that there are obvious reaction layers close to the titanium side, in contrast to the steel side, which showed no reaction layer with the silver-based braze alloy, although a coarse grain structure at the steel boundary to the silver-braze foil was formed. This coarse grain structure results from diffusion growth accompanied by recrystallization of the steel substrate at high temperature. Observations with SEM revealed that different regions were formed in the brazed area with the various chemical analyses, as indicated in figure 19.

Figure 19. SEM microstructure of brazed joint at 850°C Phase distribution in the TiAl/steel joint brazed with Ag-Cu-Zn alloy at 1173 K for 2min [72].
A large amount of Ti was dissolved from the titanium side to the brazed area close to the titanium substrate, as shown in layers B and C. The ratios between Ti and Cu in layer B are close to the CuTi phase, which formed as a thin layer, figure 19. In layer C, the ratio between Ti and Cu are closer to Cu$_2$Ti phase. Region D represents the eutectic Ag-Cu phase, while the consumption of Cu in both the CuTi and Cu$_2$Ti phases resulted in a silver-rich solid solution phase, as indicated in region E.

As the overlap width of joint increases, the Von Mises stress distribution becomes increasingly less uniform. The middle portion of the overlap contributes less to the overall load-carrying capacity of the joint, whereas the ends of the joint become overloaded. The nonuniform stress distribution in the lap joint causes a decrease in the shear strength. Increasing the temperature also led to a decrease in the shear strength of the joints, because the microstructure contained thick, intermetallic compounds and the hardness was much higher in joints brazed at 930 °C than the joints brazed at 850 °C. This caused an increase in the brittleness and weakened the joints brazed at high temperatures compared to the joints brazed at low temperatures [72].

2.8. Silver Free Filler Metals

According to Pashkov et al. [77] the cost of silver-free alloys is about half of that of alloys with 15 wt.% of silver, and 3-5 times cheaper than alloys containing 40-50 wt.% of silver. Most of the conventional silver-free alloys that could provide a comparable strength have brazing temperature ranges significantly higher than silver alloys. Only phosphorus-containing silver free brazing filler metals, SFBM, have the brazing temperature in the range of 600-750°C (1110-1380°F) comparable with silver alloys, but these phosphorus alloys produce lower strength, especially in steel joints.

Another important property of silver alloys is their plasticity in wire and strip forms. This plasticity also allows the fabrication of different preforms (rings, shims, tablets, etc.) from silver brazing alloys. Existing silver-free alloys do not possess sufficient plasticity at room temperature and require hot deformation to produce preform shapes. Hot deformation makes the manufacture of silver-free preforms so expensive that they lose a significant part of their cost effectiveness. To solve this problem a Method of rapid solidification by extraction from the melt has been introduced. The high rate of solidification ($10^4$-$10^5$ K/s) results in chemical and
microstructure uniformity of the solid product. Brittle phases (phosphides and other intermetallics) are present as very fine crystals dispersed in solid solutions. This type of microstructure facilitates further processing of the filler metals by plastic deformation to manufacture round rods, wire, or flat strip. The most important outcome is that the microstructure of the joints brazed by rapid-solidified filler metals is also uniform, without pores or cavities. Such microstructure improves the quality and strength of brazed joints. During the process a specific meta-stable micro-structure of rapid-solidified products with the grain size <10 μm is formed due to high rate of cooling. For instance, a comparison of cast and rapid-solidified filler metals P14 (Cu-P-Sn) clearly shows the advantage of the melt-quenched quasi-eutectic structure which consists of the saturated solid solution with uniformly distributed copper phosphide phases, figure 20. The wires and strips of the rapid-solidified filler metals exhibit much better plasticity than that of as-cast products due to smaller phosphides which are uniformly dispersed in the alloy microstructure. The same effect takes place in all other rapid-solidified Cu-based brazing filler metals. Available brazing filler metals manufactured by this technology are presented in table 6. Brazing filler metals P21 and P47 of the Cu-Zn-Sn and Cu-Zn-Mn systems were developed for joining carbon steels, stainless steels, and cutting tools with cemented carbides. The brazing temperature of these alloys is higher than that of standard silver filler metals, but it is lower than typical brass-based filler metals. The brazing filler metals P21 and P47 exhibit the best strength when brazing carbon or stainless steel. A special feature of the brazing filler metal P47 is that this copper-zinc-manganese alloy holds an intermediate position between Cu-Zn and Cu-Mn alloys. This alloy has the lowest melting temperature among all known silver-free and phosphorus-free filler metals due to high content of manganese.
Alloys based on copper manganese have been examined as cheaper alternatives to brazing alloys of silver-copper-zinc and for joining mild steel tubular structures [75]. Silver-based brazing alloys, which usually contain more than 40 wt % of the precious metal, play a major role in metal joining. Their relatively low melting points (600–800°C) and wide metallurgical compatibility with base alloys have led to their use in joining copper alloy and steel components. However, silver-containing brazing alloys are expensive, silver being more than 75 times the price of copper and approximately 150 times that of zinc, on a weight basis. There is a growing demand for cheaper filler metals to replace the silver brazes for joining mild steel tube.

**Table 6.** Melting and brazing temperatures of rapidly solidified filler metals [77].

<table>
<thead>
<tr>
<th>Brazing filler metal</th>
<th>Alloy system</th>
<th>Base metals to be brazed</th>
<th>Melting temperature range</th>
<th>Brazing temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>°C (°F)</td>
<td>°C (°F)</td>
</tr>
<tr>
<td>P14</td>
<td>Cu-P-Sn</td>
<td>Copper, Brass</td>
<td>640-680 (1184-1256)</td>
<td>720-800 (1328-1470)</td>
</tr>
<tr>
<td>P81</td>
<td>Cu-Zn-P-Ni</td>
<td>Copper, Brass, Steel</td>
<td>630-660 (1166-1220)</td>
<td>680-800 (1256-1470)</td>
</tr>
<tr>
<td>P21</td>
<td>Cu-Zn-Sn-Ni</td>
<td>Copper, Brass, Steel</td>
<td>780-830 (1436-1526)</td>
<td>850-900 (1562-1652)</td>
</tr>
<tr>
<td>P47</td>
<td>Cu-Zn-Mn-Ni</td>
<td>Copper, Brass, Steel, Cemented carbides</td>
<td>765-815 (1410-1500)</td>
<td>830-900 (1526-1652)</td>
</tr>
</tbody>
</table>

Jacobson et al. [75] describe the successful development of two new silver-free brazes suitable for producing tube-to-tube joints without lugs at temperatures of 800–
900°C, compatible for high-tensile strength steel tubing. Conventional low-melting-point brazing alloys are based on copper, with additions of zinc, silver, and other metals. The zinc addition lowers the melting point of copper. However, above ~46 wt-% Zn hard phases, starting with β (the CuZn intermetallic compound), become dominant and the braze is brittle. Furthermore, volatility of the alloy, on account of a significant zinc fraction, also becomes a problem (generation of bubbles and blisters in the joint). These issues place a practical limit on the amount of zinc that can be added and also the maximum melting point reduction that can be achieved by adding zinc alone. The addition of silver further lowers the melting point of copper-zinc alloys. The melting point reduction obtainable from a silver addition is considerable, down to 665°C for a silver content of 56%. Manganese lowers the melting temperature of high copper Cu-Zn-Mn alloys. The constituents are very cheap in relation to silver-containing brazes. However, for a wide range of compositions, these ternary alloys are brittle. Ni and Si, are both known to promote wetting of the braze, especially on oxidized steel surfaces; silicon also improves fluidity. However, these additions raise the melting point of the alloy and need to be offset by increasing the zinc content to bring the alloy composition as close as possible to the brittle region. The highest brazing temperature limit compatible with high-tensile-strength steel tubes is 900°C. Other essential requirements are the compatibility of the brazing alloys with brazing technique and with conventional fluxes, and their ability to consistently bridge joint clearances. Furthermore, the brazed joints have to satisfy the requisite tensile and fatigue strengths for the intended applications. Two brazing alloys have been developed that meet these requirements, 70Cu-20Zn-10Mn (wt-%; melting range, 799–925°C) and 54Cu-35Zn-6Ni-4Mn-1Si (wt-%; melting range, 850–930°C). Experiments have shown that the 54Cu-35Zn-6Ni-4Mn-1Si braze can be used with a gas flux alone, which lends itself to automated brazing. Conversely, the 70Cu-20Zn-10Mn braze requires the use of flux paste, either alone or in addition to the gas flux [75].

2.9. Concluding Remarks

In the literature, brazing techniques, important parameters and the way that they affect the joint properties have been widely investigated. Typical silver-based filler metals and silver-free filler metals have been studied and their metallurgical and
mechanical properties have been evaluated. The experimental procedures have been explained and the interpretation of results has been discussed.

In this research work, the idea of using brazing to fortify the strength and sealability of tubular joints with specific joint geometries is something new. Characterization of the mechanical and metallurgical properties of brazed joint made by a silver–based filler metal Bag 24 (Ag50-Cu20-Zn28-Ni2) in such a new application is performed with some of the same techniques reported in the literature, and some variations that have not been used before. The interpretation of the results especially in case of metallurgical characterization will be performed based on the similar methodologies that have been applied up to this time.
3. Methods, Equipments and Procedures

From the pipes, which were received, one non-expanded (V27) and three expanded (V10, V28, V29), strips of size 260 mm×12 mm and with the thickness of the pipes were cut. In order to do so, each pipe was halved longitudinally in the middle and then samples of all four available edges were cut from each half piece. At least 10 samples were taken from each of the pipes. The strips are shown in figure 21. From each pipe, 3 tensile specimens, three bending specimens, and two specimens for optical and SEM/EDX analysis were taken. The detail of preparation is discussed in the following sections.

![Figure 21. Strips cut from the pipes.](image)

3.1. Mechanical Tests (Test Specimens and Fixtures)

Because of the complexity of the pipe joints of interest, the mechanical, tensile and bending tests cannot be performed according to any available standard methods. A modified technique was therefore devised that provides an opportunity to test the brazed
joints under tensile loading. In addition, it was not possible to perform pure tensile tests on the braze because the braze interface is not parallel to the pipe axis. Considering the type of mechanical test and dimensional restrictions of the pipe joint, a test specimen with the geometry shown in figure 22 was developed. To accommodate these specimens specific fixtures are required. Initially the fixture shown schematically in figure 23 was designed. It was found that there might be some problems with bolt location with respect to the steep angle involved. The design was therefore modified, figure 24, and the problems were overcome. The details of the design can be found in the descriptions that have been supplied on each of the drawings. An overview is given in figure 25.

![Diagram](image)

**Figure 22.** Test specimen (a) as made (b) tensile specimen (c) tensile specimen with dimension.
Figure 23. Tensile specimen in recommended primary fixture.

Figure 24. Second fixture for tensile testing (both parts together).
DATE: 26 OF JANUARY 2009
TENSILE TEST FIXTURE, PARTS 1 & 2
ALL DIMENSIONS IN MM
MATERIAL: STEEL
DRILL & TAP HOLE A M8
B IS LOCATION PIN, e.g., 4MM DIA, 30MM LONG
DRILL & TAP HOLE C M6
DRILL AND TAP HOLE D M12

(a) Second fixture for tensile testing.

DATE: 26 OF JANUARY 2009
TENSILE TEST FIXTURE (PART 1)
ALL DIMENSIONS IN MM
MATERIAL: STEEL
NUMBER TO BE MADE: 2
DRILL & TAP HOLE A M8
B IS LOCATION PIN, e.g., 4MM DIA, 30MM LONG
DRILL & TAP HOLE C M6

(b) Second fixture design for tensile test (Top Part).
(c) Second fixture design for tensile testing (bottom part).

(d) Second fixture as made.

Figure 25. Second fixture detail.

During the process of making the specimens it was observed that the strips cut from the pipes bent due to the high residual stress after expansion, which could produce some problem in machining of the specimen to the final size. In order to make the machining process possible it was necessary to decrease the amount of curvature in the specimen by reducing the size of the test sample. This is more serious for the tensile test, which requires specimens that are flat, otherwise the stress distribution along the test specimen will not be uniform, and during testing, a large amount of deformation will be introduced, which invalidates the test results. The specimen was therefore re-designed as shown in figure 26.
For the bending test specimens, it was decided to prepare samples with uniform cross sectional area. As the purpose of this test is only to compare the opening process for different threaded pipe joints, the wavy state of the samples which is the result of plastic deformation /expansion process can be neglected. The specimen shape and detail of its design are shown in figure 27.
3.2. Optical Microscopy and SEM/EDX Specimens

From each pipe a strip with a suitable brazed joint was chosen and the threaded part was cut off from the strip. The whole joint was then polished and photographed under a stereomicroscope, figure 28a. Filled samples of the brazed joint were cut from the threaded section and suitable samples for optical microscopy and SEM were prepared. From each of the pipes two samples were cut and mounted in cold resin. The idea was to prevent any kind of heat treatment, which can affect the microstructure of the braze material inside the joint. After polishing and etching with 2% nital for 20 seconds it was observed that signs of over etching appeared, so it was decided to reduce the time and after re-polishing of micrographic samples, 10 seconds was found to be sufficient and was used for subsequent samples. The samples were analyzed under an optical microscope with different magnifications.
Figure 28. Photographs of specimens prepared for microscopy.
4. Results and Analysis

4.1. Brazing Filler Metal Distribution

In order to determine the uniformity of the brazing operation, i.e., how well the filler metal is distributed through the joint, the percentage of braze coverage was determined for each pipe specimen, and variations from sample to sample are shown in figure 30. The criteria for deciding whether a part of the joint is filled or not is shown in figure 29. This evaluation has performed for both sides of the joint. Non-uniform distribution of the filler metal is a common feature that was observed on all of the pipe specimens.

![Image of filled and empty parts in a joint]

**Figure 29.** Criteria for judgment about percentage of joint converge by filler material.
Figure 30. Brazed joint coverage by the filler.
4.2. Residual Stress from Expansion Process

As the specimens from the expanded pipes deform and bend when they are cut from the pipes, for the purpose of comparison, it was decided to present the amount of distortion by measuring difference in elevation for the ends of each specimen. This information is shown for each pipe in figure 31.

![Deflection of Strips (V28)](image)

![Deflection of Strips (V10)](image)

![Deflection of Strips (V29)](image)

*Figure 31. Deflection of strips cut from the pipes.*

The results confirm that non-uniform plastic deformation around the pipes can result in non-uniform stresses that act on the brazed joints at different positions around the pipe.
4.3. Optical Microscopy Characterization

The results from optical microscopy show that there is an acceptable level of wetting on the steel surfaces. In the areas with a fully brazed joint, the filler metal has a sharp interface with the base metal, which indicates acceptable wettability and a high quality joint, figure 32. No inter-diffusion of filler metal is observed in such areas.

![Figure 32. State of interfaces in threaded joined pipes.](image)

The higher magnification of the brazing filler metal revealed the same morphology and similar metallurgical structure, indicating that the same filler metal and brazing process has been used for all four pipes, figure 33. As can be seen from the figure the brazing alloy contains three different phases, which can easily be distinguished by their white, yellow, and grey colors. The different phases in the filler meal have been investigated by SEM and EDX techniques. Investigation over the length of the joints showed that in spite of good wettability, in most of the cases sections that are fully bonded are quite scarce. Lack of enough filler material required to fill the joint seems to
be a serious problem. In addition, insufficient filler material in the sealing areas (figure 3) is another problem that requires further consideration. It may be possible to solve this problem by controlling the heating and cooling cycles.

Figure 33. Magnification of filler metals in threaded joints.

Differences in the properties of the steel joint and silver based braze alloy make it difficult to grind and etch specimens properly. As the brazement is softer than the base material, in the grinding process more material will be removed from the braze, resulting in uneven surfaces which can cause problems in optical microscopy characterization. Focus can only be obtained on part of the sample; other parts appear vague and unclear. The presence of scratches on the braze material is another result of uneven surfaces. The scratches can also be the result of filler that dislodged from partially filled joints during grinding, causing scratches on the soft phases that are present, see figure 34.
Figure 34. Presence of discontinuity and defects along the joints that cause scratching problems.

The presence of the black areas in figure 33, may be the results of either evaporation of some alloying elements producing porosity, or are residuals from fluxes that have been used during the brazing process and have remained in the joint. It is important to note that the presence of pores or inclusions and the discontinuity of the filler metal along the joint can cause instability in mechanical tests, especially when tensile testing. The presence of steel islands inside the joint, figure 35, may be the result of surface treatment before brazing operation. Such features are seen quite often for the threaded joint in pipe V27. The other possibility for such a behavior can relate to the temperature cycle during brazing, which may have caused some parts of the joint to reach temperatures high enough for the filler metal to penetrate into the grain boundaries of the steel, loosening grains and causing them to float inside the brazing filler material.

Another aspect that is evident from the micrographs is the presence of significant deformation around the joint area in the steel part for pipes V10 and V27. This
deformation may be the result of machining or of plastic deformation that has occurred during pipe make up and brazing, see figure 35.

Figure 35. The presence of a great amount of deformation around the joint area (V10 & V27), presence of steel islands inside the joint (V27), black areas (V28 & V29).

In order to determine the exact reason for the presence of such deformation a part of the threaded joint without brazing filler were cut, polished, and analyzed, figure 36. The result from optical microscopy suggests that the deformation is due to the machining process. It is also clear that this deformation is not uniform over the threaded joint, see figure 37.
A 2% nital solution was used to etch the samples. From figure 33, it can be seen that this solution has properly etched the steel, but has very little effect on the braze. In order to make the brazement clearer, other etchant solutions were examined. The most effective etchant found is a solution of 5 cm$^3$ ammonium hydroxide, 25 cm$^3$ hydrogen peroxide, and 25 cm$^3$ of distilled water. This solution can strongly etch the brazing filler metal and has no effect on the steel. The presence of different phases within the braze can be distinguished with this solution. Some of the metallographic pictures are shown in figure 38. As the filler metal is the same for all the pipes it was decided to take photos from joints V28 and V29, because more filler metal was present in these samples, and take these as references for SEM/EDX analysis.
Figure 38. Optical micrographs from joints 28 & 29 with new etching solution.

In order to gain a general view on the structure in the filler metal itself, optical analysis was performed on the filler metal as well. The results are shown in the figure 39.
Figure 39. Optical microscopy analysis for the filler metal (a) cross section (b) transverse section.

The results show that the phases in the joint are similar to those in the filler before brazing operation. The presence of black points in these pictures indicates that the black areas in figure 33 can be related to the presence of impurities in the filler metal.
4.4. SEM/EDX Analysis

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) have been used to characterize the diffusion processes that occurred due to the brazing thermal cycle. SEM and EDX have also been employed to explain the distribution of alloying elements and the bonding state of the joints in more detail, both morphologically and topographically. SEM images are shown in figure 40.

Figure 40. (a) Base material steel X52 (b), (c), and (d) joint interface at high magnifications.

The steel contains two phases, pearlite and ferrite, figure 40a. The sharp interfaces which are observed in the optical microscopy results, figure 32, are shown in more detail in figures 40(b), (c), and (d). The presence of white areas surrounding some of the grain boundaries is related to etching, figure 40d. The results from energy dispersive X-ray spectroscopy for the matrix structure, the irregular white blocks, and the
eutectic-like structure are shown in figures 41 to 43. The scanning results for the interaction layer between the steel and the filler metal are shown in figures 44 and 45. Analysis has also been performed across the joint and the results are shown in figures 46 and 47. Considering these two pictures, it is important to note that according to the previous records [7, 8, 13, and 14], using similar brazing filler metals, no significant diffusion of silver into the steel has been reported. It seems that the sensitivity of the EDX equipment for silver detection is high, which should be considered in the interpretation of the results. Presence of silver on the surface of the EDX samples due to polishing or calibration problems in the EDX equipments are two potential sources of such an error. Because of ultrasonic cleaning that was performed before analysis, it seems that calibration problems are probably the main source of the error. The setting problem is probably related to the lack of proper elimination of the background silver peaks in the spectrum.

Figure 41. (a) SEM picture (b) EDX result for the matrix structure.
Figure 42. (a) SEM picture (b) EDX result for the irregular white block structure.

Figure 43. (a) SEM picture (b) EDX result for the eutectic structure.
Figure 44. (a) SEM picture (b) EDX result for the interaction layer close to the steel side.

Figure 45. (a) SEM picture (b) EDX result for the scanning across the interaction layer.
Figure 46. (a) SEM picture (b) EDX result for the interface, cross-sectional scanning.

Figure 47. (a) SEM picture (b) EDX result for the interface, cross-sectional scanning.

The analysis of the EDX line scanning results contains confusing aspects related to the presence of silver. In order to make a more reliable characterization EDX point analysis was applied. It should be noted that in point analysis the time resolution is higher (larger electron beam - sample interaction volume is achievable), which leads to a more accurate results. The difference in accuracy is related to the time spent on each point of the sample, which for point analysis was 150 seconds and for line analysis, half a second. The results of EDX point analysis are shown in figure 48.
Figure 48. (a) SEM picture (b) point analysis of position 1 (c) point analysis of position 2 (d) point analysis of position 3.

As it can be seen from figure 48, the irregular white blocks are copper-rich solid solutions of Cu-Zn-Ni-Ag. The matrix is silver with small amount of other alloying elements which have dissolved in it. The eutectic-like structure is a silver rich matrix in which strips of Cu-Zn solid solutions has formed.

Additional EDX point analysis was applied close to the steel-filler interface to investigate the inter-diffusion of elements. The results are shown in figure 49.
The results show a small mutual diffusion of iron and silver across the interface, the presence of nickel at the interaction layer and in the white irregular blocks, which are solid solutions of silver copper and zinc.

The other important conclusion is that the initial part of the silver graph in the EDX line scanning (figures 47 and 48) should be considered as a background effects.

Based on the EDX results, the phases present have been identified as shown in figure 50.
In order to develop an understanding of the approximate distance that some of the elements in the filler can diffuse; their diffusion coefficients and the diffusion lengths (see equation 11) have been calculated and are shown in table 7. Two minutes at brazing temperature (~700°C) have been considered as the basis for these calculations. D and t are diffusion coefficient and time respectively [78].

\[
\text{Diffusion length} = 2.4\sqrt{Dt}
\]  

(11)

The results show small diffusion of filler elements into the steel. This supports the conclusion that the initial silver count in the EDX line scans (figures 47 and 48) is background and cannot be interpreted as a long diffusion distance for the silver atoms into the steel.
Table 7. Diffusion coefficients and the diffusion lengths of elements in the joint at 700°C and after 2 minutes.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Diffusion Coefficient (cm² s⁻¹) [86]</th>
<th>Diffusion length (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag in Fe</td>
<td>2.74 x 10⁻¹³</td>
<td>0.16</td>
</tr>
<tr>
<td>Cu in Fe</td>
<td>4.81 x 10⁻¹⁴</td>
<td>0.07</td>
</tr>
<tr>
<td>Zn in Fe</td>
<td>4.80 x 10⁻¹³</td>
<td>0.21</td>
</tr>
<tr>
<td>Fe in Cu</td>
<td>3.18 x 10⁻¹²</td>
<td>0.54</td>
</tr>
<tr>
<td>Fe in Ag</td>
<td>2.51 x 10⁻¹¹</td>
<td>1.52</td>
</tr>
</tbody>
</table>

To gain a better idea of the interface structure and to see the sharp interfaces in figure 32 under higher magnification, additional pictures of interfaces with different magnifications are shown in figure 51. There appears to be an interaction layer with a thickness of around 2 μm and a finer grain structure than the steel and braze filler metal. Iron, silver, and nickel are the dominant alloying elements in this layer. Within the region, bonding seems to be complete and it can be seen that the joining quality of Bag24 with steel is good because there are no voids or cracks observed at the interface between the filler and the steel.
Figure 51. SEM pictures of interface with different magnifications.
4.5. Tensile Tests

The test specimens, as shown in figure 26, were prepared (figure 52) and tested using the modified testing method described in chapter 3. A Zwick100 testing machine, able to apply up to 100 kN force was used. A preload of 15N and a strain rate of 1 mm/min were applied.

Figure 52. Tensile specimens (a) before testing (b) after testing

The testing machine and the details of the specimen and fixture placement are shown in figure 53.

Figure 53. Tensile machine and fixture placement
Care should be exercised during setting the sample inside the fixture. The four bolts on each part should be tightened evenly to make sure a uniform distribution of stresses occurs during testing. Some soft metal strips (brass) were used to fix the position of the sample inside the groove of the fixture. This was done to ensure that the sample could not slide and the test results would not be affected by any unwanted displacement of the specimen inside the fixture.

In spite of reducing the size of the tensile specimens the presence of curvature was still a source of concern. After setting the specimens inside the fixture and tightening the bolts it was observed that the clearance between the parts of the fixture was not uniform. Although the amount of non-uniformity was small, it still caused some disturbances at the start of the tests. During the first test it was observed that in spite of reducing the bending moment in the specimen, by decreasing the size of the brazed area to be tested, some bending took place, which affected the result of the test. In order to prevent this behavior extra strips of metal were placed on both sides of the brazed area, which was to be tested, figure 54. It is important to note that the presence of such strips of steel will cause friction that may also cause the samples to experience shear forces.

![Figure 54. Application of steel strips to control unwanted bending.](image)

In order to reduce this effect, the steel strips and the slots on the sides of the brazed area to be tested were lubricated by grease. The results from all tensile tests and pictures of their fractured surfaces are shown in figures 55 to 64. Presence of dirt, lack of fusion, and brittle fracture were common features on the fracture surfaces.

With regard to the test results, three different sections can be distinguished in the graphs. The first section is an irregular curved shape. The second section is an almost straight line and the third section is a regular curve. The first irregular curved part is
considered to be the result of the curvature in the specimens, which during loading caused opening of the fixture to take place and is related to non-uniform gripping in the fixture. The proof of this theory can be demonstrated by the results from specimens from pipe joint V27, see figures 58 to 60. Having flat surfaces has provided the possibility of uniform gripping of the specimen in the fixture. The graphs of these tests do not have such irregular curved areas at the start of the test. The second, almost straight line section, is related to the elastic deformation of the parts involved in the system. Although it may seem to be possible to determine a modulus of elasticity from these curves, it is difficult to determine to which material or part the modulus belongs. The important point here is that although the yield strength of the filler metal is less than that of the steel, the small clearance of the joint causes the filler to be constrained and the steel parts of the joint undergo deformation. This coincides with the idea that higher joint strength can be achieved by reducing the clearance of the joint.

In some of the tests for the joints V29, V28, and V10, the tensile strength of the joint was higher than the shear strength of the steel, the steel plastically deformed and fractured under shear stresses. In the graphs for the joints V29 -1 and 3, V28 - 1, and V10 - 1 the non-linear section of high strain is due to the shear deformation of the steel pipe. What has been measured is therefore related to the shear strength of the steel. The question here is, if the steel is the part which deforms, why is it that the maximum forces in the graphs are not equal? The answer of this question can be found in the degree of precision that has been applied during the machining process, see figure 65.

Examining the specimen shows that the dimensions of the test specimens are not the same as those defined in the drawings. This not only causes variation in the forces that will cause the steel to deform under shear, but also it may reduce the strength of the steel sections below the value required to prevent shearing of the base metal. Some of these dimensional problems are shown in figure 65. The results from the tensile tests have been summarized in table 8.

Based on all of these test results and observations it can be concluded that the capability of the proposed testing procedure to measure the tensile strength of the filler, strongly depends on the strength of the filler inside the joint, which should be less than the shear strength of the steel in the geometry defined for the test specimen.
Figure 55. Tensile test results (a) test curve (b) test specimen.

Figure 56. Tensile test results (a) test curve (b) test specimen.
Figure 57. Tensile test results (a) test curve (b) test specimen.

Figure 58. Tensile test results (a) test curve (b) test specimen.
Figure 59. Tensile test results (a) test curve (b) test specimen.

Figure 60. Tensile test results (a) test curve (b) test specimen.
Figure 61. Tensile test results (a) test curve (b) test specimen.

Figure 62. Tensile test results (a) test curve (b) test specimen.
Figure 63. Tensile test results (a) test curve (b) test specimen.

Figure 64. Tensile test results (a) test curve (b) test specimen.
Figure 65. Dimensional Problems related to machining process.

Table 8. Summarized information from the tensile tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L (mm)</th>
<th>W (mm)</th>
<th>A₀ (mm²)</th>
<th>Pre-load (N)</th>
<th>Test speed (mm/Min)</th>
<th>Tensile strength (N)</th>
<th>dL at F₀₅₅</th>
<th>F₀₂₀ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V10-1</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>7910</td>
<td>3.8</td>
<td>6850</td>
</tr>
<tr>
<td>V10-2</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>4860</td>
<td>2.3</td>
<td>-</td>
</tr>
<tr>
<td>V10-3</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>8370</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>V27-1</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>1464</td>
<td>0.8</td>
<td>1390</td>
</tr>
<tr>
<td>V27-2</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>15</td>
<td>1</td>
<td>5277</td>
<td>2.3</td>
<td>4980</td>
</tr>
<tr>
<td>V27-3</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>2385</td>
<td>1.5</td>
<td>2270</td>
</tr>
<tr>
<td>V28-1</td>
<td>3.44</td>
<td>10</td>
<td>34.4</td>
<td>15</td>
<td>1</td>
<td>9490</td>
<td>6.3</td>
<td>7450</td>
</tr>
<tr>
<td>V29-1</td>
<td>4.25</td>
<td>10</td>
<td>42.5</td>
<td>15</td>
<td>1</td>
<td>11218</td>
<td>4.8</td>
<td>8850</td>
</tr>
<tr>
<td>V29-2</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>8940</td>
<td>4.2</td>
<td>7780</td>
</tr>
<tr>
<td>V29-3</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>15</td>
<td>1</td>
<td>11089</td>
<td>5.1</td>
<td>8540</td>
</tr>
</tbody>
</table>

*L & W are dimensions of the area under tensile load.
4.6. Bending Test

Bend tests have been conducted to determine the ductility or strength of a material. Bend tests for ductility differ fundamentally from other mechanical tests in that most mechanical tests are designed to give a quantitative result and have an objective endpoint. In contrast, bending ductility tests give a pass/fail result with a subjective endpoint; the test operator judges whether a surface has undergone cracking. Bending ductility tests determine the smallest radius around which a specimen can be bent without cracks being observed in the outer surface [84]. Bending strength tests (ASTM E 855), offer means of determining the modulus of elasticity in bending and the bending strength of flat metallic materials in the form of strip, sheet, or plate. Three standard bending load-deflection tests are available: the cantilever beam bend test, the three-point bend test, and the four-point bend test. Considering the geometry and the required mechanical properties of interest, three point bending is the best choice. In the three-point bend test, the test specimen is supported near each end and is loaded at one point equidistant from each support. The modulus of elasticity in bending is obtained by the measurements of load and deflection at stresses below the proportional limit. The apparatus for three-point tests consists of two adjustable supports and a means for measuring deflection and applying load, see figure 66. Specimens with standard thickness and width are prepared and tested. Load - deflection data are plotted with load as the ordinate and deflection as the abscissa. The modulus of elasticity in bending is calculated from the load increment and the corresponding deflection increment between two points on the straight line as far apart as possible [84].

Figure 66. Three-point bending apparatus.
In this research bending tests were required to evaluate the soundness of the joint in the sealing area and its capability to tolerate the tensile load exerted upon it during the expansion process. The result of the test provides a good indication of how much strength can be expected from the brazed joint as far as the expansion process is concerned. Because of the complexity of the pipe joint of interest, and restriction due to the thickness of the pipe, it was not possible to prepare standard test specimens and perform standard bending tests to determine the required mechanical properties. A new specimen and new testing criteria were therefore employed. The bending specimen design is shown in figure 27. Using the three-point bending test method the specimens are bent up to a maximum deflection, which has been chosen to be 20 mm in this experiment. It should be noted that the idea of 20 mm deflection is based on 30% expansion of the pipes with 5.5 inch (139.7 mm) outside diameter. The pipes are expanded up to 7.15 inch (181.61 mm) outside diameter, i.e., the radius of the pipe will increase up to 20 mm, which represents the maximum deflection that should be tolerated.

The result of such tests is compared with the result from a reference specimen which is of the same design, but without any thread, which is considered to be representative of a completely filled and bonded joint. The idea is to determine the modulus of elasticity for the reference specimen and to use that value to calculate the cross sectional area of the threaded specimens that was involved in carrying the applied stresses during subsequent tests. Comparing the calculated area with the nominal cross-section of the threaded specimens shows how well the filler has filled the area under bending. It should be clear that if the calculated cross-sectional area is smaller than the real cross-sectional area; the filler has not completely filled the joint at or close to the position of applied bending force.

The closer the calculated area approaches the measured area, the better the filling of the joint at the position where the bending load is applied. A bending specimen and the testing set up are shown in figure 67.
Four reference specimens, two of them from expanded pipe V29 and two from the non-expanded pipe V27 were prepared. The bending test was performed and the results are shown in figure 68 and table 9.

**Table 9.** Summarized information from the bending tests of fully steel specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Span Length (mm)</th>
<th>Width (mm)</th>
<th>s (mm)</th>
<th>Test speed (mm/Min)</th>
<th>Modulus of elasticity (E) (N/mm²)</th>
<th>dL at F&lt;sub&gt;max&lt;/sub&gt; (mm)</th>
<th>F&lt;sub&gt;max&lt;/sub&gt; (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V27-1</td>
<td>150</td>
<td>9.8</td>
<td>9.3</td>
<td>10</td>
<td>177</td>
<td>20.0</td>
<td>2890</td>
</tr>
<tr>
<td>V27-2</td>
<td>150</td>
<td>10.0</td>
<td>9.7</td>
<td>10</td>
<td>178</td>
<td>20.0</td>
<td>3350</td>
</tr>
<tr>
<td>V29-1</td>
<td>150</td>
<td>10.1</td>
<td>8.7</td>
<td>10</td>
<td>174</td>
<td>20.0</td>
<td>3430</td>
</tr>
<tr>
<td>V29-2</td>
<td>150</td>
<td>9.9</td>
<td>8.3</td>
<td>10</td>
<td>176</td>
<td>20.0</td>
<td>3180</td>
</tr>
</tbody>
</table>

The average modulus of elasticity for the reference specimen is 176 GPa. Calculation of the modulus of elasticity is based on equation 12. Specimens from the threaded pipe joints were also prepared and tested. The results of the tests are shown in figures 69 to 75, and a summary of the results is given in table 10.
Figure 68. Bending test results for the prototype steel specimens (a) V27-1 (b) V27-2 (c) V29-1 (d) V29-2.
Figure 69. V27-1 three-point bending test.

Figure 70. V27-2 three-point bending test.
Figure 71. V27-3 three-point bending test.

Figure 72. V28-1 three-point bending test.
Figure 73. V29-1 three-point bending test.

Figure 74. V29-2 three-point bending test.
Figure 75. V29-3 three-point bending test.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Span Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Test speed (mm/Min)</th>
<th>dL at $F_{max}$ (mm)</th>
<th>$F_{max}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V27-1</td>
<td>150</td>
<td>10.0</td>
<td>10.2</td>
<td>10</td>
<td>5.6</td>
<td>2140</td>
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<td>V27-2</td>
<td>150</td>
<td>9.9</td>
<td>10.0</td>
<td>10</td>
<td>10.4</td>
<td>2710</td>
</tr>
<tr>
<td>V27-3</td>
<td>150</td>
<td>9.8</td>
<td>10.0</td>
<td>10</td>
<td>4.2</td>
<td>2270</td>
</tr>
<tr>
<td>V28-1</td>
<td>150</td>
<td>10.0</td>
<td>8.4</td>
<td>10</td>
<td>15.1</td>
<td>1500</td>
</tr>
<tr>
<td>V29-1</td>
<td>150</td>
<td>9.9</td>
<td>7.7</td>
<td>10</td>
<td>4.0</td>
<td>1420</td>
</tr>
<tr>
<td>V29-2</td>
<td>150</td>
<td>9.9</td>
<td>8.5</td>
<td>10</td>
<td>12.8</td>
<td>1320</td>
</tr>
<tr>
<td>V29-3</td>
<td>150</td>
<td>10.0</td>
<td>10.2</td>
<td>10</td>
<td>10.1</td>
<td>1300</td>
</tr>
</tbody>
</table>

A range of forces should be introduced for the interval, over which the stiffness, slope of the tangents to the initial straight-line portion of the force-deflection curves, is determined. Then it is possible to calculate the actual cross sectional areas that were involved in the tests. According to reference [85] the cross-sectional area that carries the
stress during loading in a three – point bending test is calculated as follows:

\[
A = \frac{0.25L^3M}{ED^2},
\]

(12)

where L is the support span (mm), M is the slope of the tangent to the initial straight-line portion of the force-deflection curve (N/mm), E is the modulus of elasticity in bending (N/mm²), and D is the test specimen thickness (mm).

Fitting a line through the linear elastic part of the curves, the stiffness (M) of each specimen can be determined. Using eq. (12) and taking E to be the average modulus of elasticity 176,250 MPa, the effective areas under the bending stresses are calculated. The nominal cross-sectional areas have also been measured on the specimens. Comparing these two cross-sectional areas gives a measure for the degree of filling that exists in the joint were the test load is applied. The results of the calculation and measurements for the tested specimens are shown in table 11. According to these results V29-1 is the joint with the highest level of filling and the joint V27-1 is the specimen with the lowest level of filling.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stiffness (N/mm)</th>
<th>Span Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Nominal cross sectional area (mm²)</th>
<th>Calculated cross section area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V27-1</td>
<td>968.34</td>
<td>150</td>
<td>10.0</td>
<td>10.2</td>
<td>102.0</td>
<td>44.6</td>
</tr>
<tr>
<td>V27-2</td>
<td>1213.1</td>
<td>150</td>
<td>9.9</td>
<td>10.0</td>
<td>99.0</td>
<td>58.1</td>
</tr>
<tr>
<td>V27-3</td>
<td>1230.8</td>
<td>150</td>
<td>9.8</td>
<td>10.0</td>
<td>98.2</td>
<td>58.9</td>
</tr>
<tr>
<td>V28-1</td>
<td>691.35</td>
<td>150</td>
<td>10.0</td>
<td>8.4</td>
<td>84.0</td>
<td>46.9</td>
</tr>
<tr>
<td>V29-1</td>
<td>779.94</td>
<td>150</td>
<td>9.9</td>
<td>7.7</td>
<td>73.2</td>
<td>63.0</td>
</tr>
<tr>
<td>V29-2</td>
<td>684.87</td>
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<td>9.9</td>
<td>8.5</td>
<td>84.7</td>
<td>45.1</td>
</tr>
<tr>
<td>V29-3</td>
<td>549.69</td>
<td>150</td>
<td>10.0</td>
<td>10.2</td>
<td>102.0</td>
<td>25.2</td>
</tr>
</tbody>
</table>

It should be noted that even if the joint is filled, if the bonding is not strong enough to endure the elastic region of deformation the result will be a smaller calculated cross-sectional area compared to the measured area. This means that calculating the effective area (the area that carries the bending load) and comparing it with the nominal area contains information about the quality of the bonding as well. If a joint is filled properly
(the nominal and calculated areas are close to each other) then it makes sense to measure the maximum loading capacity of the joint at the loading area, which is an indication of the joints capability to tolerate the expansion process.

In order to develop an understanding of the level of loading capacity that can be expected from a joint, the maximum applied forces in the bending test performed on fully steel specimen are considered to be the maximum achievable values. The closer the measured strength of the joint is to these values, the better the performance of the joint with regard to the expansion process. For the non-expanded samples the reference value is the average of the maximum forces for the reference specimens V27-1 and V27-2 (3120 N) and for the expanded samples it is the average for the reference specimens V29-1 and V29-2 (3305 N).

Referring to the results of tables 10 and 11, it can be concluded that for joint V27-1 with the lowest degree of filling, the maximum force was 2140 N, which is 68.6% of the maximum achievable force over a defined maximum deflection value.

In order to make an easier comparison between the results for the specimens, the quality of the coverage, which is the ratio of the calculated area to the nominal area, and a force ratio, which is defined as the ratio of the maximum applied force in the bending test to the maximum force achieved from the fully steel specimen, have been calculated and presented in table 12.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Nominal cross sectional area (mm²)</th>
<th>Calculated cross section area (mm²)</th>
<th>Quality of coverage</th>
<th>F max (N) Fully steel specimen</th>
<th>F max (N)</th>
<th>Force ratio (Bonding quality)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V27-1</td>
<td>102.0</td>
<td>44.6</td>
<td>43.7</td>
<td>2140</td>
<td>3120</td>
<td>68.6</td>
</tr>
<tr>
<td>V27-2</td>
<td>99.0</td>
<td>58.1</td>
<td>58.7</td>
<td>270</td>
<td>3120</td>
<td>86.9</td>
</tr>
<tr>
<td>V27-3</td>
<td>98.2</td>
<td>58.9</td>
<td>60.0</td>
<td>2270</td>
<td>3120</td>
<td>72.8</td>
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<tr>
<td>V28-1</td>
<td>84.0</td>
<td>46.9</td>
<td>55.8</td>
<td>1500</td>
<td>3305</td>
<td>45.4</td>
</tr>
<tr>
<td>V29-1</td>
<td>76.2</td>
<td>63.0</td>
<td>82.7</td>
<td>1420</td>
<td>3305</td>
<td>43.0</td>
</tr>
<tr>
<td>V29-2</td>
<td>84.7</td>
<td>45.1</td>
<td>53.2</td>
<td>1320</td>
<td>3305</td>
<td>40.0</td>
</tr>
<tr>
<td>V29-3</td>
<td>102.0</td>
<td>25.2</td>
<td>25.0</td>
<td>1300</td>
<td>3305</td>
<td>39.3</td>
</tr>
</tbody>
</table>

It should be clear that a high percentage of coverage quality is not a sufficient condition to obtain a high quality of bonding. This is especially seen in joint V29-1. It
should also be noted that according to these results, a higher force ratio cannot directly be interpreted as an indication for a higher percentage of coverage for the joint. The reason for this is that the bonding quality is not linearly related to the percentage of coverage. That is why each of these two criteria (force ratio and percentage of coverage) should be interpreted separately. In other words, we should not expect that a 100% bonding quality is required for 100% coverage quality or that 100% coverage quality implies 100% bonding quality.

It is recommended to first calculate the percentage of coverage and then, in the case that it is close to the measured value, it makes sense to determine the force ratio, which is a representation of the bonding quality. It should also be mentioned that for judging whether or not a calculated area is close to the measured value a minimum acceptable percentage should be defined. This percentage should be specified by using the expansion process to determine the acceptable value above which the joint will perform suitably. Using this methodology it would be possible to predict whether or not any pipe joint will withstand the expansion process without expanding the joint.

The bending test described here may be an alternative for the expansion tests that are performed to find out whether or not a pipe joint is suitable for the required application. The other usage of the proposed test can be to determine the changes in the bonding quality for the expanded joints. This follows from any changes in the force ratio after the expansion process. Comparison between the coverage area before and after expansion is an indication of how much disbonding has occurred during the expansion process. The sealability of the joint should be determined after the expansion process; hence the proposed bending test should be performed on the expanded specimens.
5. Discussion

5.1. Brazing Filler Metal Distribution

When the threaded brazed joints were analyzed under the stereomicroscope it was seen that in the joint V27, there exists only a very small part that could be used for characterization of the material. Only the inside end of the threaded joint, the sealing area, contained filler metal that could be tested, figure 28c. In addition distribution of the filler metal is highly inhomogeneous, the joint is empty over most of its length and it seems there hasn’t been enough material to fill the joint. This joint was not expanded and after cutting strips, no deformation or deflection were observed.

For the pipe V28 there is some filler metal that can be observed with the naked eye, however the distribution of the filler is again highly inhomogeneous and a large part of the joint is empty. An interesting point about this joint is the presence of some changes in the design of the joint, which seems to have been applied to make the pre-placement of the brazing filler wires possible (only at the outside sealing part). Although this can be effective for increasing the amount of filler that will be available, the results of the process show that the filler material is not generally in the sealing areas. Most of the filler has flowed inside the joint leaving empty holes, which considering the reduction of load carrying capacity of the joint and concentration of stresses at this point, may be unacceptable, figures 28d and e. The reason why the filler has moved toward the inner parts of the joints can be related to the position of the pipes during the joining operation. It may be the case that the process was carried out with the pipe in a horizontal position.

For the pipe V10, there is some filler metal in both inside and outside sealing parts of the joints. It seems that the filler has been used on both sealing parts and considering the better distribution of filler it can be the case the pipe has been brazed horizontally (figure 28b).

For V29, non-uniform distribution is quite clear. Some of the joints just opened up as they were cut from the pipe. In comparison with other pipes there is more filler material in the joints and in some cases, the filler has flowed out of the joint in the internal sealing area, figure 28e. In most of the joints the inner sealing area is not completely filled and there are some, where there is nothing in the joint at all. The problem of empty holes is quite clear in this case as well. The over flow of the filler
metal may be the result of application of some extra filler metal in or around the sealing area.

5.2. Optical Microscopy, SEM and EDX Analysis

The presence of three phases is distinguishable in the macrographs (figures 38 and 76). In order to interpret these pictures it is necessary to consult the binary and ternary phase diagrams related to the filler material being used. Filler metal, Bag-24 has 50% Ag, 28% Zn, 20% Cu, and 2% Ni. The diagrams are shown in appendix A. Considering the position of filler elements in the periodic table, it can be concluded that they have close atomic size which will facilitate diffusivity (substitutional diffusion). The brown area in the figure 76, which is the major constituent in the filler, is likely to be a silver rich matrix. The irregular white blocks, which seem to be of high stability, having no reaction with the etching solution and no color changes, are copper rich solid solutions of Cu-Zn-Ag-Ni. Considering the solubility of zinc and copper in silver, some zinc and copper has been dissolved in the matrix. The yellowish phase is likely to be a eutectic solution of copper and silver, the only eutectic reaction that is possible in this system. The EDX results (figure 48d) show the presence of small amounts of other alloying elements like zinc, indicating that this is not a pure silver-copper eutectic.
Another important feature that should be considered in the micrographs in figure 38 is the presence of a non-continuous irregular white phase at the interface. As mentioned this is a copper rich phase and according to the phase diagrams, pure copper has a melting temperature of about 1085 °C. So it seems that during the brazing operation, which is performed around 700 °C, as soon as diffusion of elements takes place this will be the primary phase that will solidify. As the solidification is more likely to take place heterogeneously, because of the lower activation energy that is involved, the steel walls are primary nucleation sites and will be the appropriate places for this phase to form. The result will be the growth and formation of these white blocks in the structure. It should also be noted that during cooling the surface will cool faster and will provide more undercooling which can be another reason for copper rich phases to solidify preferentially at the surface. Considering the low concentration of nickel in this composition, it is not easy to predict how this element will behave in such a system. But, because of the high solubility of nickel in iron it is likely that this element has migrated toward the steel parts of the joint and is dissolved in the interface.
The analysis of the filler metal, figure 39, shows that the irregular white blocks are primary phases that have been produced during the manufacturing process.

5.3. Tensile Test

Among the results of the tests, the deviation of specimen V10-3 from the general rule of a curve comprised of three-sections (explained in section 4.5) is noteworthy. This was the first test performed without strips of steel applied to prevent initial bending of the specimen. It is clear from figure 57 that after the initial curved part, the deformation is accompanied by some rotation of the specimen section that should be tested under tensile load, see figure 77. The rotation will continue until the edges of this section touch the base material. At this point the state of deformation returns to a tensile mode and almost pure elastic behavior continues. There is an interesting feature associated with specimens V10-2, V27-1 and V27-3 (figures 56, 58, and 60), which is the lack of any plastic deformation related to the steel base metal. As shown, the fractured parts show no bending of the steel. The braze metal is therefore the material that has been tested to failure under tensile load in these specimens. Analyzing the fractured surfaces of these specimens shows that lack of filler material, the presence of dirt, and lack of fusion are common problems. It should be noted that the presence of such defects caused a reduction of the brazed joint strength and made it possible to test under pure tensile load with the proposed test method. Another interesting point occurs when the tensile strength of the brazed joint approaches the shear strength of the base metal.

![Figure 77. Rotation of the specimen section that should be tested under tensile load.](image-url)
It is expected that under such a condition a combination of decreasing and increasing load behavior will be observed. The decrease is considered to be related to the shear yield strength of the steel, which causes plastic deformation of the base metal to take place and the flow of dislocations on the slip plains in steel to be activated. As the test was performed under a constant strain rate, this caused a reduction of the applied force. At the same time, the occurrence of the plastic deformation causes strain hardening, and after a while, when the interlocking of dislocations takes place, the force required to keep a constant rate of deformation during the test increases. The increase in the load continues until the tensile strength of the filler metal in the joint is exceeded and the joint fails. Joints V29-2 and V27-2 show examples of such a behavior, figures 59 and 63. It can be concluded that in order to make the technique suitable for stronger joints, i.e., joints with uniform distribution of the filler and without any impurity or dirt, it is necessary to reduce the size of the area under tensile loading, below the 40 mm² that was considered here. This also reduces the bending moment involved during the test and it should increase the accuracy of the results.

It is important to note that there are at least two main reasons that prevent simple measurement of all the mechanical properties such as yield strength, modulus of elasticity, and ductility from this test results. Firstly, because of the geometry of the test specimen and the position of the brazed joint, it is not possible to define an initial gauge length or to use an extensometer to measure the strain. Secondly, as there are lots of steel parts such as the hooks, machine jaw, and fixture parts, involved in the test system, any cross head displacement in the machine will be the response of all parts involved to the applied force and it will not be the brazing filler displacement alone. The presence of a small amount of bending and lack of enough filler material which has left some part of the joint empty are also parameters that make the values obtained for the displacement difficult to interpret. However, it may be possible to determine the mechanical properties by using the cross head displacement and a correction factor that can account for all deformations which are present from all other parts in the system. This can be done by making the same specimens according to figure 26 from a metal (steel or aluminum), performing the test and comparing the result with that from a standard tensile specimen. Reduction of joint area to be tested and making sure that there is enough filler material in that area are other important factors that should be taken into consideration. It is also important to make sure that the thickness of the filler
material in the joint is acceptable so that restriction from the steel base material will not affect the deformation of the filler. Only under such conditions can the mechanical properties of the filler be determined. It is clear that in the areas of the joint with small clearances, the tensile strength of the joint is the only interesting property that can be measured. In order to have a general understanding about the required dimensions of the test specimen the yielding criteria have been used. The free body diagram of the specimen (figure 78) and the analysis are shown below.

![Free body diagram of the tensile test specimen.](image)

**Figure 78.** Free body diagram of the tensile test specimen.

As the distance L is very small it is possible to assume the $A_s$ surfaces are under pure shear and $F_1$ is negligible. According to the Tresca yield criterion a material starts yielding when its effective stress, according to Tresca, reaches a critical value known as the uniaxial yield strength $\sigma_y$.
Tresca criterion [32]:

\[
\sigma_{\text{Max}} - \sigma_{\text{Min}} = \sigma_y = 2K,
\]

(13)

\(\sigma_{\text{Min}}, \sigma_{\text{Max}}\) are the maximum and minimum of the principal stresses and \(K\) is the yield strength of the material in pure shear. The material should show tensile yielding at cross section \(A_s\) but not shear yielding at cross section \(A_n\). Here \(A_s\) and \(A_n\) are the cross sectional areas on which shear and normal forces are applied (see figure 78). This means that the shear stress at cross section \(A_s\) \((\tau)\) should be less than the shear yield strength of the material \(K\), and the tensile stress at the cross section \(A_n\) \((\sigma)\) should be higher than the uniaxial yield strength of the material \(\sigma_y\). See eqs. (14) and (15).

\[
\tau = \frac{F}{A_s} < K,
\]

(14)

\[
\sigma = \frac{F}{A_n} > \sigma_y,
\]

(15)

Using these two equations and considering the specimen has a width \(W\), we have:

\[
\frac{F}{\sigma_y} > A_n \Rightarrow F > A_n \sigma_y.
\]

(16)

and

\[
\frac{F}{K} < A_s \Rightarrow F < KA_s.
\]

(17)

hence

\[
A_n \sigma_y < KA_s.
\]

(18)

substitution from equation 13,

\[
2A_n < A_s.
\]

(19)

with \(WH = A_s\) and \(WL = A_n\)
New specimens of aluminum were made and tested according to this criteria, figure 79 and table 14. The results have been compared with the tests for the standard dog-bone specimens, figure 80 and table 13. The outcome of the tests shows that a good approximation of the joint strength can be obtained by this method. The proposed testing method yields results that match the uniaxial tensile test data to within 6.5%. These results are shown in figures 81 to 83.
Figure 79. Aluminum tensile specimens.
Figure 80. Tensile test results and specimens for aluminum.
Table 13. Summarized information from the tensile tests for aluminum dog-bone specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$S_0$ (mm$^2$)</th>
<th>$E_{mod}$ (MPa)</th>
<th>Pre-load (N)</th>
<th>Test speed (mm/Min)</th>
<th>Tensile strength (MPa)</th>
<th>$\varepsilon$ at $F_{max}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-1</td>
<td>28.26</td>
<td>61.2</td>
<td>15</td>
<td>1</td>
<td>349</td>
<td>10.7</td>
</tr>
<tr>
<td>AL-2</td>
<td>28.26</td>
<td>74.8</td>
<td>15</td>
<td>1</td>
<td>307</td>
<td>9.7</td>
</tr>
<tr>
<td>AL-3</td>
<td>28.26</td>
<td>54.4</td>
<td>15</td>
<td>1</td>
<td>350</td>
<td>17.1</td>
</tr>
<tr>
<td>AL-4</td>
<td>28.26</td>
<td>62.9</td>
<td>15</td>
<td>1</td>
<td>324</td>
<td>11.9</td>
</tr>
<tr>
<td>AL-5</td>
<td>28.26</td>
<td>63.1</td>
<td>15</td>
<td>1</td>
<td>342</td>
<td>15.3</td>
</tr>
</tbody>
</table>

The results from table 13 show an average of 335 MPa for the tensile strength of the aluminum that was tested. The results from the new aluminum specimens are given in table 14. Two of these specimens went under shear deformation, see figures 81b and 82b. The specimen without shearing showed a close value, 313 MPa, for the tensile strength of the aluminum that can be obtained from the modified testing technique.

It should be noted that even in the case of shear deformation in the new aluminum specimens, the values predicted for tensile strength, 300 and 318 MPa are close to the average value. It should also be considered that the shear deformation of aluminum in the specimens with $L$ dimension of 2 and 1.7 mm (table 14) is the result of non-accurate (manual) preparation of the specimen which can be avoided by using an appropriate mechanized cutting method.

Specimens of the brazed joint V28 with proposed criterion ($H > 2L$) were prepared and tested. The results are shown in the figures 84 and 85.

Table 14. Summarized information from the tensile tests for aluminum specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$L$ (mm)</th>
<th>$W$ (mm)</th>
<th>$A_n$ (mm$^2$)</th>
<th>Pre-load (N)</th>
<th>Test speed (mm/Min)</th>
<th>Tensile strength (N)</th>
<th>$dL$ at $F_{max}$ (mm)</th>
<th>$F_{max}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>2</td>
<td>10</td>
<td>20</td>
<td>15</td>
<td>1</td>
<td>6007</td>
<td>3.4</td>
<td>300</td>
</tr>
<tr>
<td>AL</td>
<td>1.7</td>
<td>10</td>
<td>17</td>
<td>15</td>
<td>1</td>
<td>5229</td>
<td>2.8</td>
<td>318</td>
</tr>
<tr>
<td>AL</td>
<td>1.5</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>1</td>
<td>4696</td>
<td>2.2</td>
<td>313</td>
</tr>
</tbody>
</table>

*L & W are dimensions of the area under tensile load.
Figure 81. Tensile test results (a) test curve (b) test specimen Aluminum 2 x 10 mm.
Figure 82. Tensile test results (a) test curve (b) test specimen Aluminum 1.7 x 10 mm.
Figure 83. Tensile test results (a) test curve (b) test specimen Aluminum 1.5 x 10 mm.
Figure 84. Tensile test results (a) test curve (b) V28 test specimen $1.7 \times 9.8$ mm.
Figure 85. Tensile test results (a) test curve (b) V28 test specimen 1.7 x 9.5 mm.
It is important to note that a small amount of elongation in the braze is required to produce a high amount of strain and this will cause the fracture to occur after a small displacement. This explains why the plastic deformation before the fracture is so small. The other important aspect is that the length and the width of the area under tensile load (10 x 1.5mm) are much larger than the thickness of the braze which cause a triaxial stress state and increases the strength of the braze material. Triaxiality prevents deformation and promotes void formation and ultimately results in ductile fracture. In order to develop an understanding of the mechanism that cause failure, the fracture surfaces have been investigated under a scanning electron microscope. The results are shown in figures 87 and 88. A typical fracture surface is shown in figure 86.

Figure 86. Fractured surface, V28 test specimen 1.7 x 9.8 mm.
Figure 87. Fractured surface under SEM with different magnifications, V28 specimen 1.7 x 9.8 mm.
Figure 88. Fractured surface under SEM with different magnifications, V28 specimen 1.7 x 9.5 mm.

Ductile fracture is caused by overload and, depending on the constraint, can often be recognized immediately from macroscopic examination of a failed specimen. If there is little constraint there will be a significant amount of contraction before failure occurs.
In the case of interest, that is with very high constraint, a ductile fracture may occur without noticeable contraction. In such cases the only difference on a macro-scale with brittle fracture is the reflectivity of the fracture surface, which tends to be dull for ductile fracture and shiny and faceted for a brittle fracture. On a microscopic scale ductile fracture of materials occurs by a process known as void coalescence, which results in a dimpled appearance of the fracture surface. Dimple shape is strongly affected by the type of loading. Fracture under local uniaxial tensile loading usually results in formation of equi-axed dimples. Failures caused by shear will generate elongated or parabolic shaped dimples that point in opposite directions on matching fracture surfaces. Tensile tearing produces elongated dimples that point in same direction on matching fracture surfaces [33]. See figure 89.

Figure 89. Dimple shape affected by type of loading [33].
Accordingly, the presence of equi-axed dimples in the fractographs is a clear sign that ductile fracture is the dominant failure mechanism. This not only is a strong indication of the validity of the proposed testing procedure, but also guarantees that the idea of neglecting the shear forces in calculating optimized cross sectional area for the specimen has been a valid assumption. The presence of equi-axed dimples is a sign that the surface has been under a uniaxial tensile load. It is important to note that the presence of a big difference in dimple sizes as seen in figure 88 can probably be the results of existing inclusions or the presence of phases with different mechanical properties or both. With the presence of inclusions void formation can start earlier (at lower stress levels) and dimples become larger. In addition it makes a difference whether the dimple formation occurs in the silver matrix or in the irregular white blocks or in the yellowish eutectic phase. In order to see the importance of this difference the hardness of phases has been measured and the results are shown in table 15. The hardness measurement has been performed with the application of 10 g force on the indenter. There are two important features that should be considered. Firstly, the relative high spread in the hardness of the eutectic and the silver matrix, which is related to the distribution of the eutectic phase and its surrounding environment and to the spread of other phases in the silver matrix. Secondly, it should be noted that the small sizes of the existing phases make it impossible to measure the hardness of a phase without the effects coming from other phases surrounding that phase.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Vickers Micro Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>White irregular blocks</td>
<td>226.7</td>
</tr>
<tr>
<td>Eutectic phase</td>
<td>230.1</td>
</tr>
<tr>
<td>Silver matrix</td>
<td>186.4</td>
</tr>
</tbody>
</table>

The other important aspect to note is that the apparent spread of the results for the tests on the brazed joint V28, figures 84 and 85, is probably the result of doing the test on areas \( A_n \) with different position on the test specimens (the orientation of the
threaded joint differs along its profile). The difference in orientation of the threads and the thickness of the filler will consequently result in such spreads. The distribution of the metallurgical phases is not uniform along the threaded sample and this is another important source of spread in mechanical testing results. It should be clear that for comparison purposes the specimens with the same position of the test areas ($A_n$) should be prepared and this will minimize any kind of discrepancies arising from such factors.

In order to have a better understanding about the fracture behavior of the filler, extra optical analysis was performed. The state of the interfaces, the thickness of the braze and the place where fracture has occurred is shown, see figures 90 and 91. The results show that when the interface bonding is of full coverage and free of defects, the fracture takes place in the filler itself and in the case that there are discontinuities or impurities which disturb the bonding, the fracture occurs in the interface area.

The thickness of the brazed layer in the joint for each fractured specimen has been measured. As it can be seen from figures 90 and 91 for the joint with the strength of 560 MPa a thickness of 559 microns is seen and for the joint with the strength of 480 MPa a thickness of 134 microns has been measured. The fact that the thickness of this layer, the joint clearance, is smaller in the sample with lower strength is probably related to existing defects and the dominant presence of a phase with weaker mechanical properties. This feature has already been explained in relation to the dimple size.
Figure 90. V28 test specimen 1.7 x 9.8 mm top a, b, c, d and bottom parts e, f, g, h of fracture surfaces.
Figure 91. V28 test specimen 1.7 x 9.5 mm top a, b, c, d and bottom parts e, f, of the fracture surfaces.
6. Conclusion

Characterization of brazed joints on threaded X52 steel pipe connections was performed. Suitable mechanical testing techniques have been devised. Metallurgical and mechanical properties of the joints were determined and the interrelation of these properties was investigated. The main conclusions from the research are:

- The results from the tensile test demonstrate the capability of the designed fixture and the proposed testing method to measure the tensile strength of the threaded joints.
- For the expanded pipe joints, depending on the position where the tensile load is applied, a range of ultimate tensile strengths up to 560 MPa are achievable.
- For application of the proposed tensile test, it is important to make sure that the selected areas ($A_n$) are oriented parallel to the axis of the pipe so that the presence of any shear components of the force is minimized.
- Using the proposed bending test and the defined parameters (bonding quality and coverage quality), it is possible to predict the soundness (bonding strength and filling state) of the joints, and the joint ability to tolerate the stress state exerted upon it during the expansion process.
- The results from optical microscopy and SEM/EDX analysis show that a (Ag-Cu+Zn) eutectic-like structure, (Ag-Cu-Zn-Ni) solid solution and a silver rich matrix are the dominant metallurgical phases present in the expanded pipe joints V10, V28 and V29.
- The presence of inclusions/chemical residuals, the non uniform distribution of metallurgical phases and the variation of the thread orientations through the joint can strongly affect the mechanical properties that are achieved, and cause scatter of the results.
- The results from EDX analysis show a small inter-diffusion of iron into the braze filler and a small diffusion of silver into the steel. No diffusion of other alloying elements into the steel has been detected.
• No intermetallic phases were detected, either by optical microscopy or SEM/EDX analysis techniques.

• In most of the samples the filler metal distribution in the joint is highly non-uniform and the filler cannot be found in the place that it is expected to be, i.e. the inner or the outer sealing areas at the end of the joint.

• Lack of enough filler material to fill the joint is a common problem for all the pipe joints. This problem is so serious in the pipe joint V27, that analysis of the non-expanded joint was impossible.

• The results from optical microscopy characterization show that the filler Bag24 has a good wettability on the steel surface, which makes it possible to provide appropriate bonding properties (good interface reaction with no cracks and defects) with the steel surface during brazing.

• The results from optical microscopy characterization show that there are no adverse effects (penetration of filler and damaging of base metal) on the steel structure.

• The results from optical microscopy on the fracture surfaces show that when the bonding is complete with full coverage, the fracture takes place in the filler itself. In the case when defects and impurities disturb a complete bonding the fracture occurs at the interface area.

• Measurements of the deflection in the expanded samples (V10, V28 and V29) show that considerable residual stresses exist in the expanded pipe joints. These should be considered when reliable performance of the joint in corrosive environments is of interest.

• The results from stereo microscopy show that the changes in the design of joints V28 and V29 (drilled holes) to make the pre-placement of the brazing filler wires possible has brought about the presence of empty holes in the joint structure that can strongly reduce the mechanical performance of the joint as far as the load carrying capacity of the joint is concerned.
7. Recommendations

1. In the case that controlling the filler is not feasible in vertical brazing, it is recommended to use two types for filler metal with different melting behavior e.g. pure copper and Bag24, so that the one with higher melting temperature can control the flow of the other.

2. It is recommended to use additional brazing filler by placing layers of filler metal on the internal surface of the pin & box parts of the threaded joint, close to the pin end and out of the joint. This, with the help of gravity and capillary action could feed the joint and solve the problem of lack of filler material in the joint.

3. Consider rapidly solidified filler metals for improved economics.

7.1. Further work

Because of a limitation in time and lack of samples some extra evaluation is required in order to complete this research. The general concepts that should be addressed are:

- The effect of the expansion process on the threaded joints and the resulting changes in the mechanical properties of the joint due to work hardening and plastic deformation. This will provide information that can help to determine whether or not the mechanical performance of the joint can be improved by controlling the filler distribution and keeping the filler in the critical parts of the joint.

- The compatibility of the filler metal Bag24 and the steel pipe X52 especially in the environments that they are expected to be used, should be examined. This is particularly important when a corrosive environment is considered.

- The fatigue resistance of the joint in torsion and other dynamic loading that are applied during drilling operation or well completion process should be evaluated.
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Appendix A
Figure 92. Phase diagrams.