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Mechanical Properties of High Temperature Vacuum Brazed HSS on Structural Carbon Steel with Simultaneous Heat Treatment

Mehanske lastnosti visokotemperaturno vakuumsko spajkanih in istočasno toplotno obdelanih spojev

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The high temperature vacuum brazing process, at the HSS austenitization temperature makes it possible to carry out simultaneously the brazing of HSS on structural carbon steel and heat treatment. The advantages of this process are: increased strength of brazed joints and toughness of the part, optimum hardness and cutting edge strength for a given combination working part/cutting tool. The process is economical when used in modern mass production methods, irrespective of the number of metals to be joined and heat treated. The adaptability makes the process so economical.

Key words: high temperature vacuum brazing, hardness, microstructure, shear strength, tensile strength, vacuum heat treatment

Postopek visoko temperaturnega vakuumskega spajkanja v enokomorni vakuumski peči s homogenim plinskim ohlajanjem pod visokim tlakom vodimo v območju avstenitizacije hitroreznih jekel. Prednost tako izdelanih rezilnih orodij je predvsem v doseganju želene žilavosti nosilnega dela iz konstrukcijskega jekla, v doseganju optimalne trdote rezila izdelanega iz hitroreznega jekla ter njegove odpornosti proti otopitvi pri dani kombinaciji del/orodje. Trdnostne lastnosti vezne plasti so odvisne od dodajnega materiala, tehnologije izdelave in pogojev vakuumske toplotne obdelave. Uporaba tega postopka je ekonomična, če moramo spojiti in vakuumsko toplotno obdelati le nekaj ali pa večje število orodij.

Ključne besede: visoko temperaturno vakuumsko spajkanje, trdota, mikrostukture, strižna trdnost, natezna trdnost, vakuumska toplotna obdelava

1 Introduction

High temperature vacuum brazing is a method of joining of metals by means of heat and filler metal in vacuum at temperatures above 900°C, yet below the melting point of the joined metals, and with no use of fluxes. The products are defect-free joints with very high bonding strength that can even reach the strength of the joined metal in many cases (e.g. steel, nickel or cobalt alloys).

The high temperature vacuum brazing of HSS on structural carbon steel with simultaneous heat treatment is performed in single chamber vacuum furnaces, with uniform high-pressure gas quenching at the austenitization temperature of HSS. In this work high temperature brazed joints of HSS and structural carbon steel with simultaneous heat treatment were investigated. Two brazing alloys based on Ni-Cr-Si and copper were applied as filler metals. The shear strength of an overlap joint and the tensile strength of a but joint as well as, the microstructure and fracture surface were investigated.

The advantages of the process are, the requested toughness of the carrying part from structural carbon steel and the optimum hardness and cutting edge strength of HSS for the given combination of working part/cutting tool. Such mechanical properties of cutting tools manufactured in the conventional way from HSS can only be obtained by an additional tempering operation.

Other advantages of the high temperature vacuum process are energy savings, the omittance of expensive tool steels and their cleaning, as well as, few parts are to be joined or hundreds of thousands when it is economical to use vacuum brazing with modern mass production methods. The adaptability makes vacuum brazing of increasing use in the metal-joining processes.

2 Basic factors affecting the mechanical properties of the brazed joint

The strength of the filler metal is one of the main factors influencing the strength properties of the brazing joint, since it is a direct measure for the strength properties of the joints. Therefore, joints brazed with nickel-base filler metal are stronger than those brazed with copper-base filler metal.

The narrow joint clearance causes a high capillary filling pressure; therefore, the gap should be parallel over the whole length of the joint. Only in this way by increased capillary filling pressure the filler metal can be aspired into the gap. The most favourable joint clearance for high vacuum temperature brazing is approximately 0 - 100 μm, when measured at the brazing temperature. **Figure 1** shows schematically the relation between joint clearance and the tensile strength of the joint for flux brazing and high temperature brazing[1].

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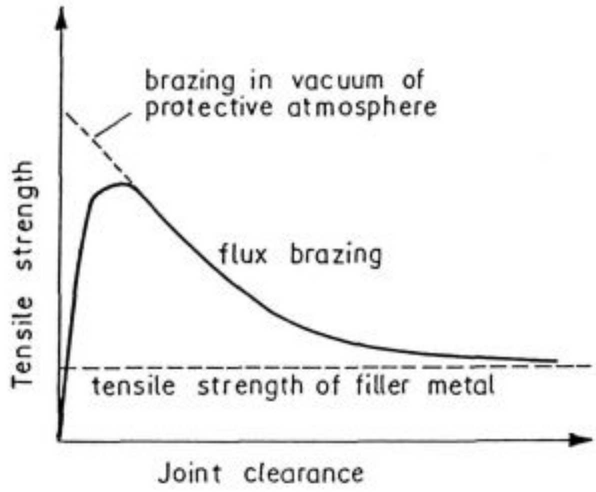

Figure 1: Relation between the joint clearance and the tensile strength of the joint[1]

Slika 1: Odvisnost med širino špranje in natezno trdnostjo spoja

The tensile strength of a brazing joint increases with the increasing tensile strength of the base metal, if all other conditions such as filler metal and joint clearance are the same, (**Figure 2**). The tensile strength of the base metal has no influence on the shear strength of the brazing joint, (**Figure 3**). In this case, only the properties of the filler metal are dominant. The tensile strength of the brazing joint decreases with the increase of the brazing contact area, (**Figure 4**). This can be explained by the fact that the chance for the formation of blowholes increases with the contact area, especially if the flow path for the filler metal also increases. However, the loadability of the piece is increased by increasing the contact surface of brazing.

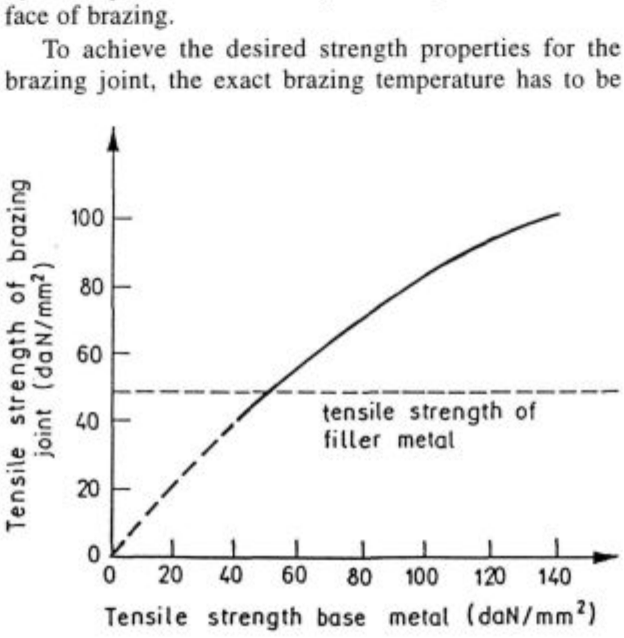

Figure 2: Tensile strength of the brazing joint as a function of the tensile strength of the base metal[1]

Slika 2: Natezna trdnost spajkanega spoja v odvisnosti od natezne trdnosti osnovne kovine

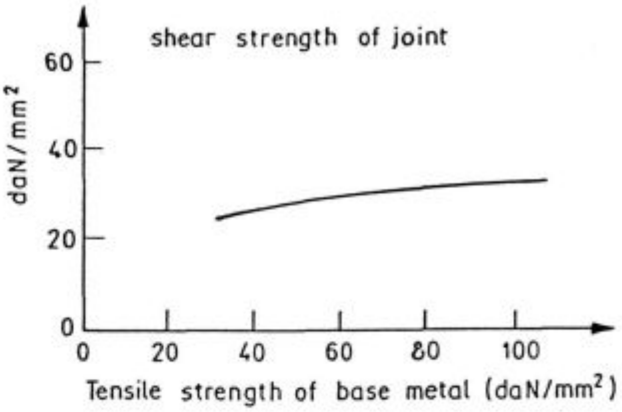

Figure 3: Shear strength of the brazing joints as a function of the tensile strength of the base metal[1]

Slika 3: Strižna trdnost spajkanega spoja v odvisnosti od natezne trdnosti osnovne kovine

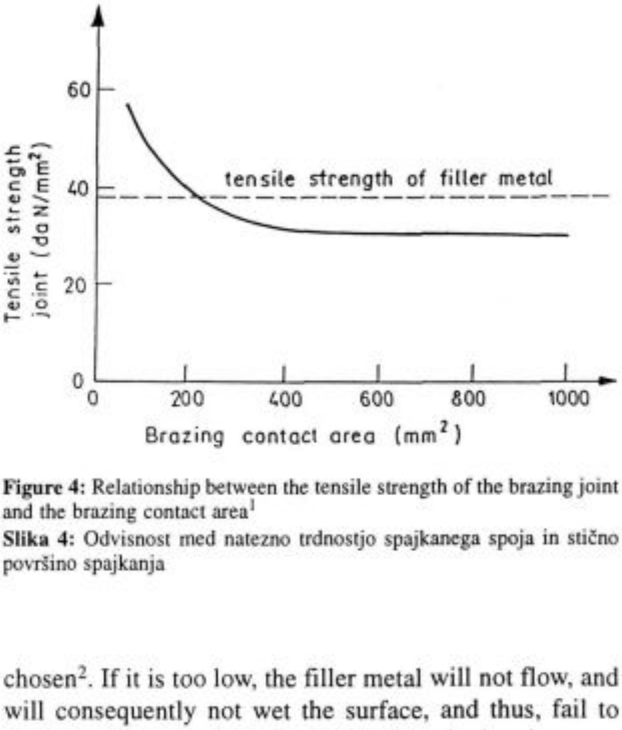

Figure 4: Relationship between the tensile strength of the brazing joint and the brazing contact area[1]

Slika 4: Odvisnost med natezno trdnostjo spajkanega spoja in stično površino spajkanja

To achieve the desired strength properties for the brazing joint, the exact brazing temperature has to be chosen[2]. If it is too low, the filler metal will not flow, and will consequently not wet the surface, and thus, fail to bond the base metal. On the other side, the brazing temperature must not be exceedingly high, as the alloyed elements in the filler metal might evaporate or undesired changes of the base metal could take place.

In some cases longer soak time at the brazing temperature after the melting of the filler metal also contributes to increase the strength properties. In this case, the diffusion zone is larger that results in higher strength properties of the joint as long as no brittle intermetallic phases are formed[2]. Investigations have shown that even with small quantities of impurities[1] in the filler metals, the mechanical properties are decreased significantly. The brazing joint becomes brittle because of the formation of brittle layers between the filler metal and the base metal.

3 Experimental procedure

Experiments were performed on high temperature vacuum brazed joints of the HSS W. No. 1.3343 and M15 (AISI) and the structural carbon steel W. No. 1.1141 (DIN) with simultaneous heat treatment. The filler metals used in this process were two brazing alloys manufactured by the Nicrobraz Wall Colmonoy firm (LM, 30) based on Ni-Cr-Si and water-atomised copper powder with the required brazing properties, (**Table 1**).

Table 1: Chemical composition of base metals and filler metals (in wt%)

Tabela 1: Kemijska sestava jekel in dodajnih materialov (v ut.%)

Material	C	Si	Mn	P	S	Cr	W	Mo	V	Co
1.3343	0,89	0,35	0,29	0,018	0,018	4,2	6,3	4,9	1,8	-
1.1141	0,14	0,27	0,32	0,007	0,012	0,1	-	-	-	-
M15(AISI)	1,5	-	-	-	-	4,5	6,5	3,5	5,0	5,0
LM	7% Cr; 4,5% Si; 3;0% Fe; 2,1% B; max.0,06% C; bal. Ni									
30	19% Cr; 10,2% Si; max.0,10% C; bal. Ni									
Cu	99,8% Cu									

To get a higher strength of the joint or to make the fixturing of parts to be brazed easier, a lap joint should be selected. This joint should be designed to obtain the same stability under load of the joint and of the base metal. The lap length is then function of the tensile strength of the base metal and the shearing strength of the joint:

$$U = \frac{R_m \cdot t}{\tau} \tag{1}$$

where U = length of the lap in mm,

R_m = tensile strength of base metal in $\mathrm{Nmm^{-2}}$,

τ = shearing strength of the joint in $\mathrm{Nmm^{-2}}$,

t = thickness of base metal in mm.

If, in addition, a safety factor and an impairment of the joint caused by small brazing errors is taken into account, then the length of the lap should be 3 to 6 times the thickness of the base metal. Generally, three times the base metal is sufficient for metals of low tensile strength; six times should be used for metals of high tensile strength[1].

The but joint is used for thicker parts (t > 2 mm) if a lap joint is not possible[1]. In contrast to soldering, the stability under load of this type of joint is often sufficient for practical use if the parts are brazed.

Experiments[3] were performed on shear specimens with single and fourfold overlap, (**Figure 5**). The lamellae from HSS and structural carbon steels were, finely ground after rough machining. Measurements showed that the surface roughness $R_a = 0.44$ µm in the longitudinal direction was equal for both surfaces.

The test specimen with but joint shown in **Figure 6** was used for the tensile test.

For the brazing of the shear and tensile test specimens with the but joint the clearance of 80 µm was chosen. The brazing temperature was 1120°C for specimens brazed with the filler metals LM and Cu, and 1160°C for those brazed with the filler metal 30. After diffusion heat treatment, the specimens were cooled in nitrogen flow at the pressure under 5 bar abs, and than double tempered at 550°C, (**Figure 7**). The brazing was performed in a vacuum 5×10^{-2} mbar. Shear and tensile specimens with but joints were used for metalographical and mechanical research.

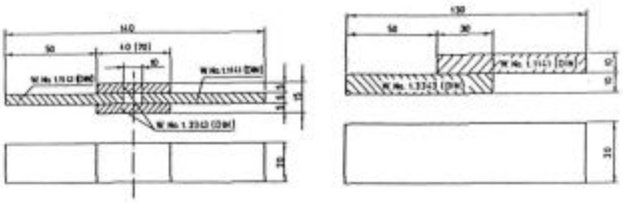

Figure 5: Shear specimens with single and four-fold overlap

Slika 5: Strižna preizkušanca z enkratnim in štirikratnim prekritjem

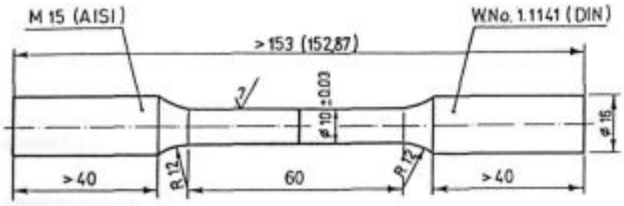

Figure 6: Tensile test specimen with but joint

Slika 6: Natezni preizkušanec s čelnim spojem

For the investigation of endurance of brazing joint, two paper knives with the dimensions of 425x117x10 mm and one knife with the dimension 560x117x10 mm, were manufactured from HSS W. No. 1.3343 steel and their bearing parts from the steel W. No. 1.7131 (DIN) steel, (**Figure8**). The filler metal marked LM was used for these knives and considering the knives' shape, a lap joint with 80 µm clearance was chosen. The brazing temperature was 1190°C. After diffusion heat treatment, the knives were cooled in a nitrogen flow at a pressure under 5 bar abs, followed by double tempering at 540°C, (**Figure 7**). The brazing was performed in a vacuum, 5×10^{-2} mbar.

4 Results and discussion

4.1 Mechanical tests

Next to the required properties of structural carbon steel and HSS, the most important property is the bond strength between them. Mechanical tests were performed on fourteen shear specimens with a single and four-fold overlap and length of the lap of 2 to 6 times the thickness of the base metal and three tensile test specimens brazed with LM and Cu filler metal.

The joint clearance for high temperature vacuum brazing was among 50-70 µm for the specimens brazed with fillers LM and 30, and 20-50 µm for the specimens

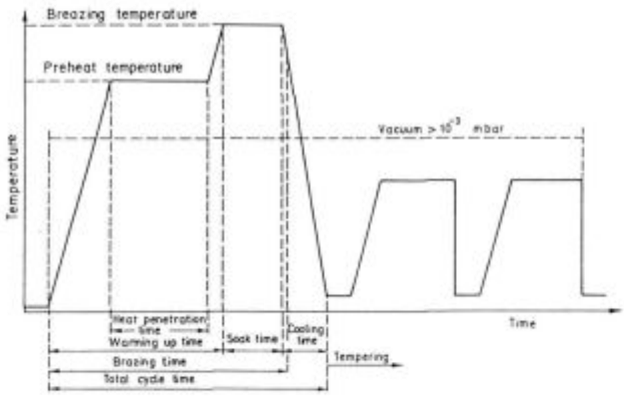

Figure 7: High temperature brazing with simultaneous heat treatment process model

Slika 7: Model visoko temperaturnega vakuumskega spajkanja z istočasno toplotno obdelavo

brazed with the copper filler. Data regarding specimens characteristics and the shear strength obtained by the Instron tensile testing machine are summarised in **table 2**.

Table 2: Specimens characteristics and the shear strength

Tabela 2: Karakteristike preizkušancev in strižne trdnostip rekrovnih spojev

Sample	Filler metal	Overlap	Length of the lap	Shear strength Nmm^{-2}
A/1	LM	four-fold	3 x t	> 30
A/2*	LM	four-fold	3 x t	27
A/3	LM	four-fold	6 x t	> 30
A/4*	LM	four-fold	6 x t	18
A/5	LM	single-fold	3 x t	> 71
A/6	LM	single-fold	2 x t	> 210
B/1	30	four-fold	3 x t	> 30
B/2*	30	four-fold	3 x t	27
B/3	30	four-fold	6 x t	> 20
B/4	30	single-fold	3 x t	> 60
C/1	Cu	four-fold	3 x t	> 32
C/2	Cu	four-fold	6 x t	> 62
C/3	Cu	single-fold	3 x t	> 66
C/4	Cu	single-fold	2 x t	> 205

* Samples fractured in bond layer; C/1- the middle lamellae made from W. No. 1.1141, end lamellae made from W.No. 1.3343; C/2 all lamellae made from W.No. 1.3343, because of gliding in the chucks, there was no destruction of the sample; C/3- all lamellae made from W. No. 1.1141.

Results in **table 2**, show that rupture of samples, in general, appeared in the structural carbon steel and not in the bond layer, **(Figure 9)**, since the shear strength of brazed joints was greater than the tensile strength of the structural carbon steel. The sample where the middle lamellae were from the steel W. No. 1.1141, was an exception since the fracture appeared simultaneously on both middle lamellae.

The shear strength is dependent upon the overlap shape and the lap length. The maximal shear strength was obtained on samples with a single-fold overlap and with the lap length 2 times the thickness of the base metal. On samples brazed with filler metal LM slightly higher values were obtained.

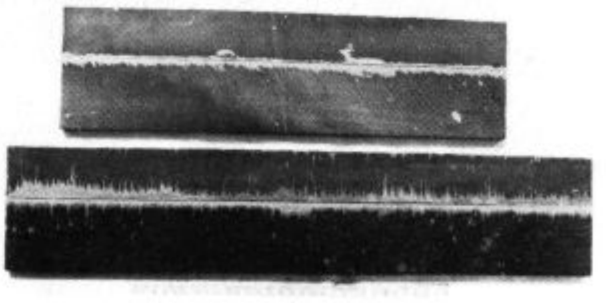

Figure 8: Paper knives manufactured by high temperature vacuum brazing with simultaneous heat treatment process to achieve a hardness of 64 Hrc

Slika 8: Noža za rezanje papirja izdelana po postopku visoko temperaturnega vakuumskega spajkanja in istočasno toplotno obdelana na 64 HRc

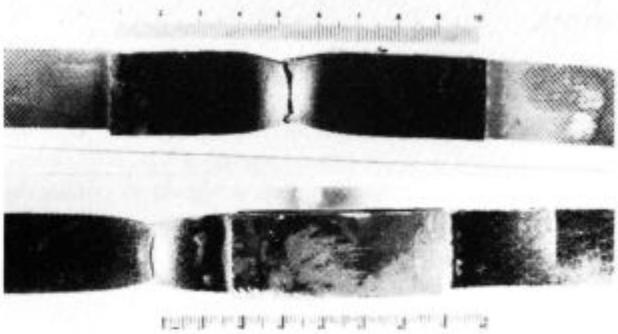

Figure 9: Shear specimens B/1 and C/1 with a four-fold overlap after the tensile test

Slika 9: Strižna preizkušanca B/1 in C/1 s štirikratnim prekritjem po trgalnem preizkusu

After vacuum heat treatment that corresponded to austenitizig and tempering temperatures for HSS M15 (AISI), the strength of the tensile test specimen with but joint was a little lower than that for structural carbon steel. The fractures propagated mostly within the bond layer and partly also in structural carbon steel and HSS. By tensile tests, the strength of specimens with but joint was strongly influenced by defects in the bond layer (sample C/8*). During tensile tests we did not notice any elongation or reduction of area on the samples. Results of tensile tests are presented in **table 3**.

Table 3: Strength of the tensile test specimen with but joints

Tabela 3: Natezne trdnosti čelno spajkanih preizkušancev

Sample	Filler metal	R_e (Nmm^{-2})	R_m (Nmm^{-2})
A/8	LM	330	445
C/7	Cu	340	475
C/8*	Cu	325	345

* defects in the bond layer

After mechanical tests, a metallographical examination was performed. On the single or four-fold overlap

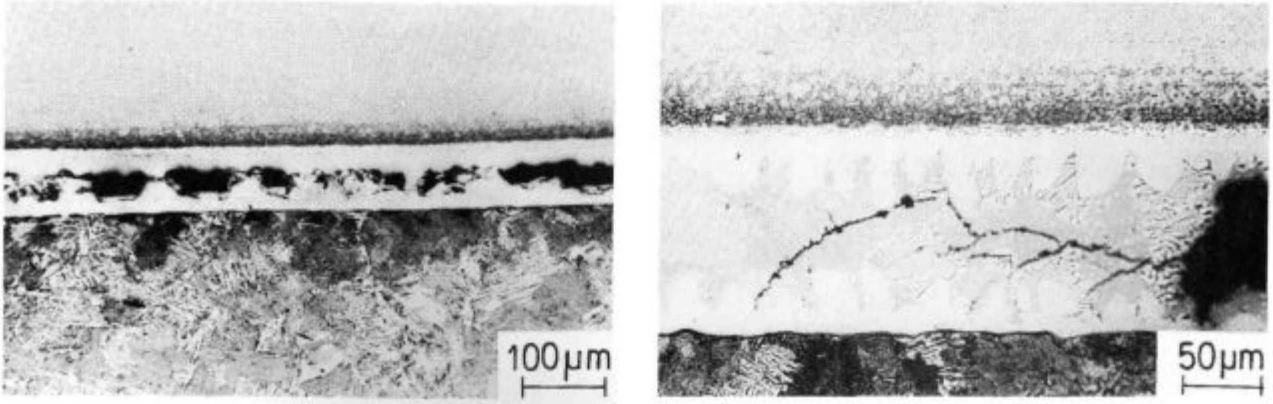

Figure 10: Initial microcrack area propagating through the eutectic phase is in the microporous regions, sample A/2
Slika 10: Inicial za nastanek mikrorazpok, ki potekajo po eutektični fazi, so mikroporozna mesta, preizkušanec A/2

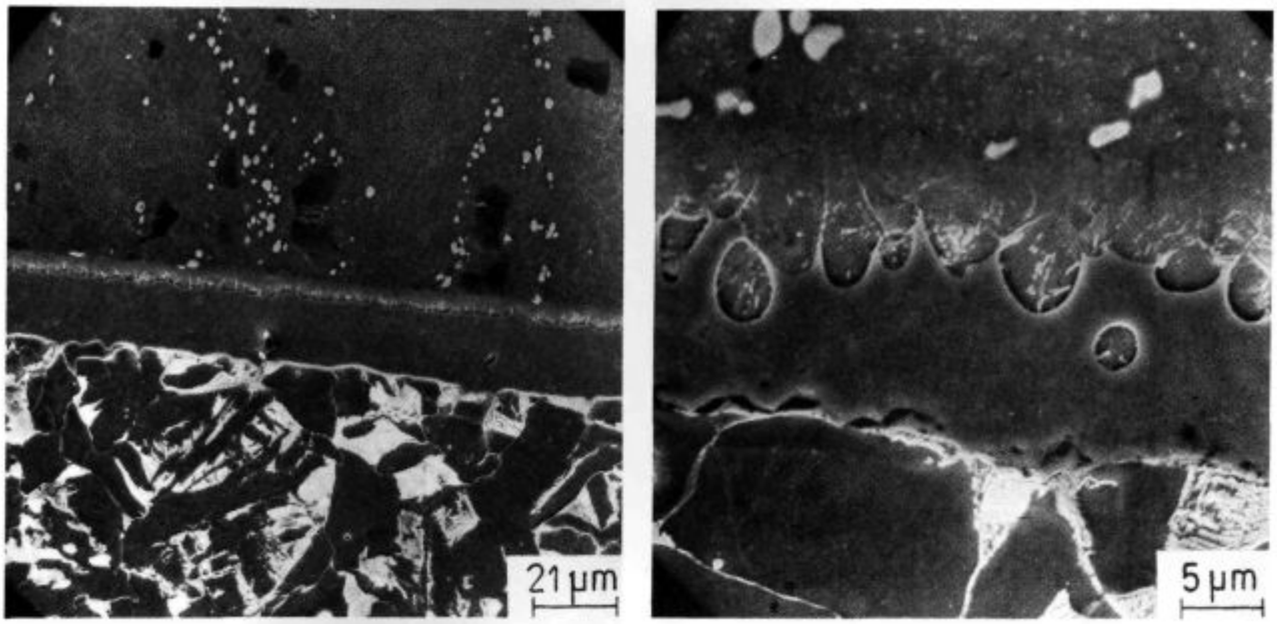

Figure 11: Microstructure of the bond layer in specimen C/7
Slika 11: Mikrostruktura vezne plasti na preizkušancu C/7

specimens, where fractures appeared in the structural carbon steel, only sporadic microcracks were found in the bond layer. On specimens with fracture in the bond layer, areas with microporosity were noticed, without exception, where microcracks initiated. On specimens brazed with the fillers LM and 30, the fracture cracks propagated through the eutectic phase of the bond layer, (**Figure 10**).

As mentioned above, the diffusion of carbon from HSS to structural carbon steel took place; and consequently, the microstructure along the bond layer/structural carbon steel consisted of pearlite and bainite. On specimens brazed with copper, cracks appeared at the bond layer/structural carbon steel, respectively, (**Figure 11**). Tensile test specimens fractured in this region, as well. Although carbon is not soluble in copper, the diffusion of carbon from HSS throughout the copper bond layer to structural carbon steel cannot take place, the mi-

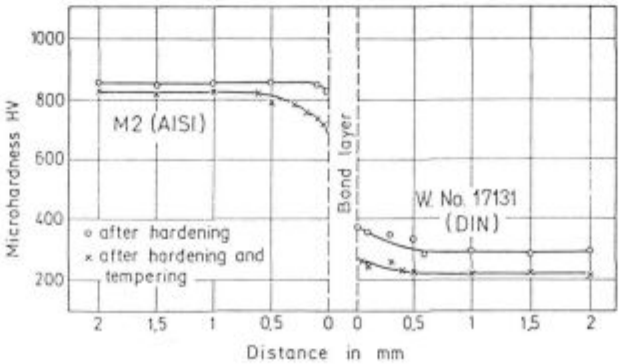

Figure 12: Vickers microhardness on transition from the bond layer to HSS and structural carbon steel
Slika 12: Potek mikrotrdote HV na prehodu iz vezne plasti v hitrorezno in konstrukcijsko jeklo

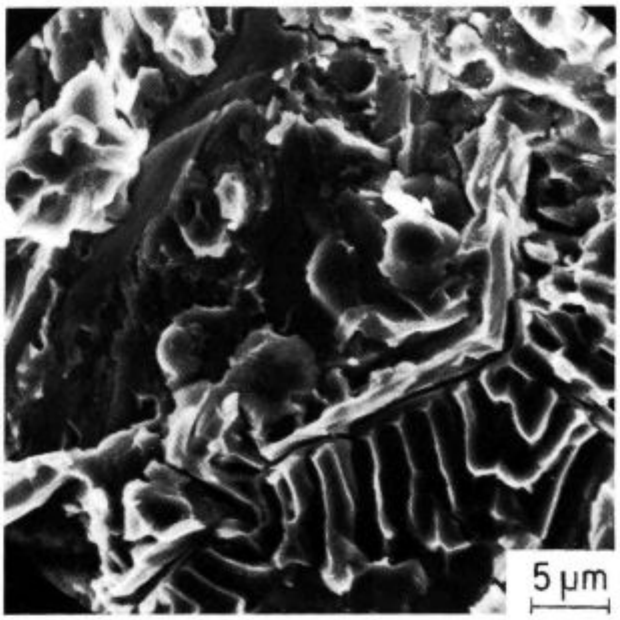

Figure 13: Fracture through an area of eutectic and austenite phase, sample A/8
Slika 13: Prelom preko eutektika in avstenitne faze, preizkušanec A/8

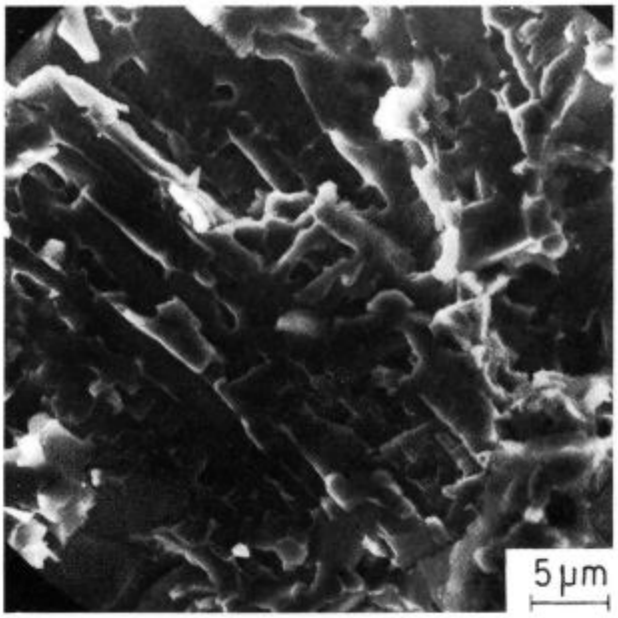

Figure 14: Fracture surface of the specimen B/2
Slika 14: Prelomna površina preizkušanca B/2

crostructure along the bond layer/structural carbon steel consisted of ferrite and bainite with traces of pearlite.

On the paper knife, the microhardness was measured across the bond layer to HSS and the structural carbon steel. The diffusion annealing was carried out with the aim to affect hardness at its transition across the bond layer and **Figure 12** shows the microhardness profile obtained. It shows that the HSS hardness is decreased, while it is increased in the structural carbon steel.

The morphology of fracture surfaces is very heterogeneous. On the specimens brazed with the fillers LM and 30, it was possible to identify fracture surfaces that propagated in dendrit's area from those propagated in the eutectic phase and in austenite, **(Figs 13 and 14)**.

Ductile fracture on specimens brazed with copper propagated mostly within bond layer, **(Figure 15)**. Inclusions of copper oxide were found in the dimples.

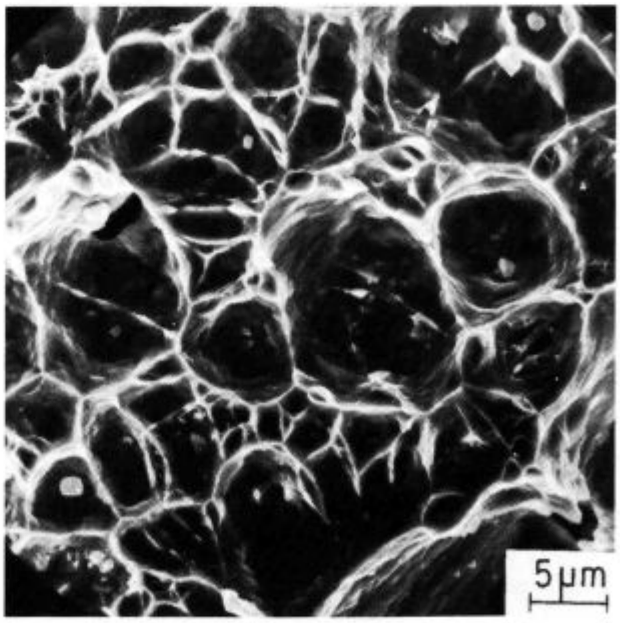

Figure 15: Fracture surface of the specimen C/7 brazed with Cu
Slika 15: Prelomna površina preizkušanca C/7 spajkanega s Cu - v jamicah so vključki bakrovega oksida

4.2 Microstructural characterisation

The used filler metals, structural carbon steel and HSS were examined by optical and scanning electron microscopy. The microstructure of the W. No. 1.1141 (DIN) structural carbon steel consisted of ferite-pearlite and bainite with a hardness of 145 HV10. The microstructure of the W. No. 1.3343 HSS consisted of a matrix of tempered martensite containing small carbide precipitates. The size of austenite grains was among 17 and 13 SG depending on the austenitization temperature and the hardness 64 HRc.

Figure 16 shows the microstructure of the bond layer between the HSS and the structural carbon steel on hardened and tempered specimens A/1 and B/2. The specimens were brazed with the fillers LM and 30.

In the bond layer polygonal grains formed because of the diffusion during brazing. The diffusion at the HSS/bond layer border seams to be quicker; therefore, more of this phase is found in the bond layer along the HSS. Along the structural carbon steel/bond layer, the bond layer was homogenous. The specimen B/2 was examined by SEM, **(Figure 17)**.

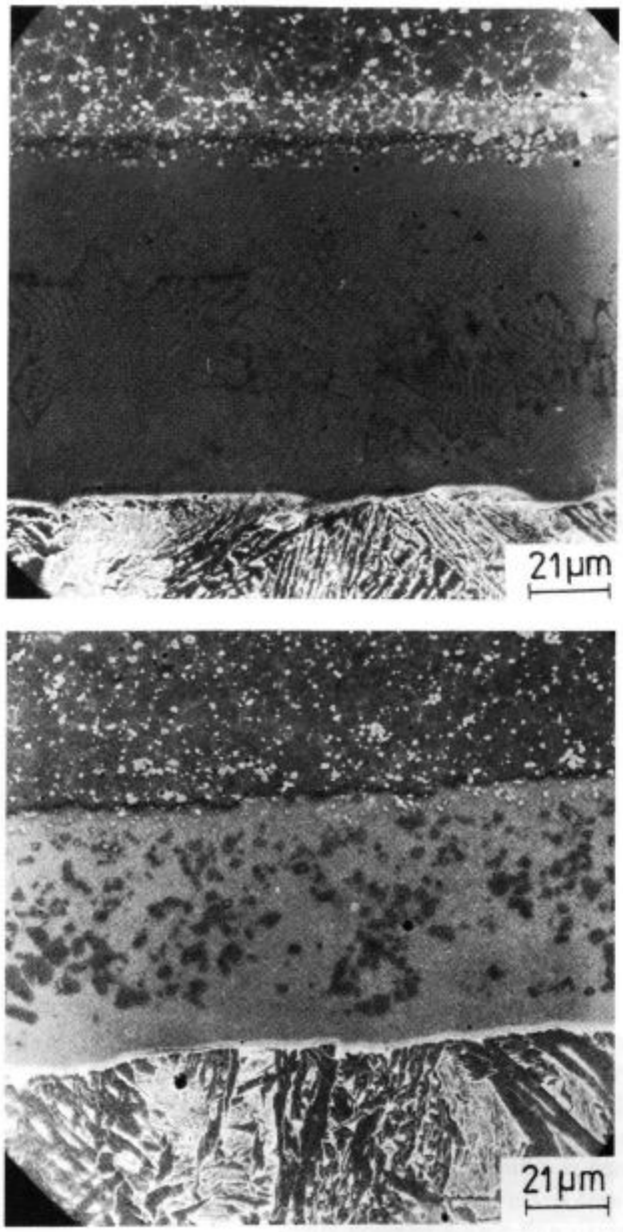

Figure 16: Microstructure of the high temperature brazed and simultaneously heat treated joints of HSS and structural carbon steel, samples A/1 and B/2
Slika 16: Mikrostruktura vezne plasti na preizkušancih A/1 in B/2

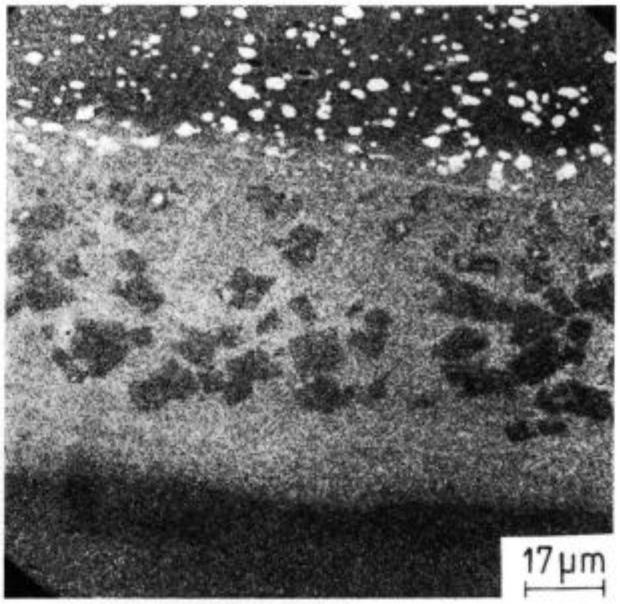

Figure 17: SEM micrograph of high temperature brazed joint, specimen B/2
Slika 17: Mikrostuktura vezne plasti preizkušanca B/2 posneta s SEM

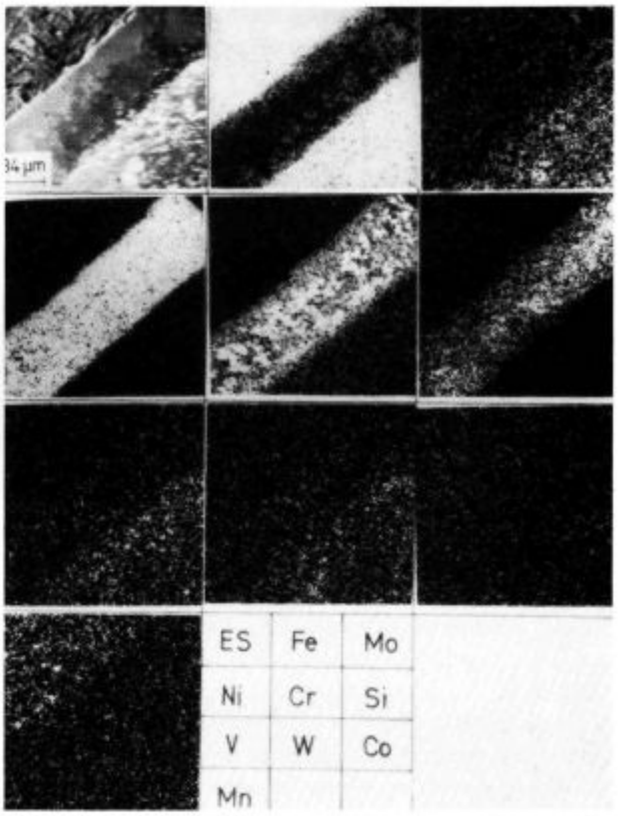

Figure 18: Distribution elements in the bond layer, sample B/2
Slika 18: Porazdelitev elementov v vezni plasti na preizkušancu B/2

A detailed investigation in EPMA showed that the larger polygonal grains present along the central line of the bond layer were a phase solidification grains rich in Cr, containing also Ni and Si with traces of W, Mo and V. The smaller grains were carbides, **(Figure 18)**. The intermetallic phase was hard. The measured microhardness was 500-600 HV. The average matrix microhardness was 195 HV.

In the microstructure at the HSS/bond layer border, the effects of the diffusion processes were clearly noticeable. In the thin layer of HSS only carbides particles were noticed, martenzite matrix was transformed because of diffusion into austenite. This microstructure was very similar to that in the bond layer, **(Figure 17)**.

At the bond layer/structural carbon steel border, diffusion of Cr, Ni and Si to structural carbon steel occurred. The hardened and tempered samples brazed with filler metal LM and 30 showed along this border a thin layer rich in carbon, (**Figure 16**) with microstructure consisting of a small amount of pearlite and bainite. The diffusion of carbon was more rapid on the samples brazed with the filler LM.

The microstructure of W. No. 1.7131 (DIN) structural carbon steel used for bearing part of paper knives consisted of tempered martensite and bainite. Austenite grains were coarse, due to the high austenitization temperature. The microstructure of the W. No. 1.3343 HSS consisted of a matrix of tempered martensite containing small carbide precipitates and the size of austenite grains of 14 SG. The microstructure of the bond layer was identical as in hardened and tempered samples brazed with filler metal LM.

5 Conclusion

Mechanical tests and metallographic observations were carried on high temperature vacuum brazed and simultaneously heat treated shear specimens with single and four-fold overlap and tensile test specimens with but joint. Two Ni-Cr-Si brazed metals as well as copper served as filler metal. During the heat treatment, rapid diffusion processes occurred between the liquid and the hard phase, especially along the HSS border. By use of Ni-Cr-Si based filler metal the formation of intermetallic phases, eutectic phases and carbides in the bond layer, and a net of eutectic carbides and voids on the austenite net along the bond layer/HSS border, were observed.

The mechanical properties of the bond layer depend on specimen design, manufacture and heat treatment conditions. The bond layer must be as thin and as homogenous as possible and must shows no porosity or microcracks. Intermetallic phases and carbides cannot be eliminated, due to the speed of the diffusion processes, which are very high on the HSS heat treatment temperature.

6 References

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