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CRACK INITIATION AND GROWTH UNDER CYCLIC LOADING IN STEEL, HARDFACING WITH ALUMINUM BRONZE BY TIG WELDING METHOD

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Abstract: *The article presents a study of fatigue properties and microstructure of steel, hardfacing with CuAl8Ni2 (aluminum bronze). The TIG welding method is used. The coated specimens are made of structural steel C45. Some structural transformations were found in the zone of the added metal, the fusion zone and the heat affected zone (HAZ). The research includes determination of microhardness and macrostructural changes in individual zones. Axial resonance fatigue tests under symmetrical loading cycle (R=-1) were carried out, on ultrasonic fatigue machine at 20kHz, observing the crack initiation and growth in the specimen body. Micro and macro structural studies were carried out in the crack initiation zone.*

Key words: *TIG welding; aluminum bronze; fusion zone; heat affected zone; crack growth; gigacycle fatigue.*

1. INTRODUCTION

Hardfacing is an efficient and economical surfacing technique, extensively employed by heavy industries to remediate worn components in service or to enhance wear characteristics of components prior to use. In an effort to economize on expensive non-ferrous alloys, the production of bimetallic components is gaining popularity through a process, involving the deposition of aluminum bronze onto structural steel. The application of Cu coatings has the additional advantage of eliminating spark formation, which could potentially lead to the ignition of air-vapor mixtures, generated by the rotation of agitators in tanks, for example.

In [1] comparative review of ferrous and nonferrous hardfacing alloys is made. All aloys are wear and corrosion resistanct. Among non-ferous hardfacing materials, Co, Ni based alloys and bronzes are mentioned. Components suitable for hardfacing with aluminium bronze are such, working in ambient conditions, including gears, cams, and cold drawing dies. Cobalt and Ni alloys are aplicable for elevated temperatures. Another review shows the arc welding deposition methods, used in ship reparing with their advantages and disadvantages [2].

One of the recent review papers [3] discusses issues and challenges in hardfacing practices, such as dilution and cracking. According to authors there hasn‘t been sufficient research conducted to establish a comprehensive understanding of certain phenomena, such as cracking, distortion, and residual stress distribution. There is a lack of experimental research, addressing the impact of these factors on component‘s performance. Most of the hardfacing research papers are connected with abrasion ware characteristics and corrosion properties.

Wear resistance after slide burnishing and the effect of heat treatments on fatigue properties of aluminium bronzes, alloyed with Fe (Cu-Al-Fe), is discussed in [4], [5]. Different wear mechanisms under dry and boundary lubrication conditions, and positive effect from burnishing operation are investigated in [4]. Different heat treatment regimes are found out to give the highest fatigue strength and the lowest wear [5].

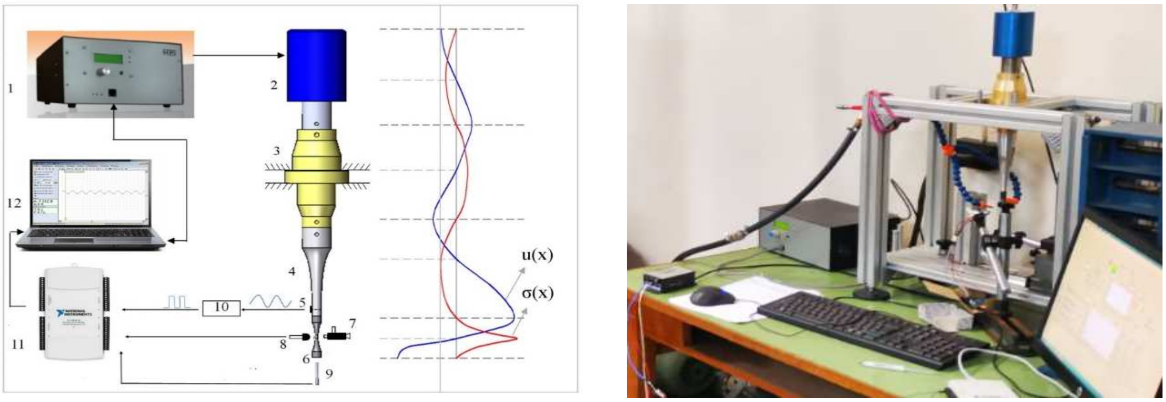

Fig. 1 . Block scheme (left) and working machine (right) of ultrasonic fatigue testing device, designed, and assembled in Strength of materials lab, TU-Varna.

1 – Ultrasonic generator (MPI Ultrasonics); 2- High power transducer (MPI Ultrasonics); 3- Booster (Gold 1:1.5); 4- Sonotrode; 5-PVDF foil for strain monitoring; 7- Vortex tube; 8- Temperature sensor; 9- Displacement sensor (Philtec D20); 10- Comparator for cycle counting; 11- NI 6082 multipurpose ADC (sample rate 200kHz); 12 – Computer with LabView routine for control and monitoring.

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Aluminum bronze type, is one of the most prevalent Cu-based alloys, renowned for its high mechanical strength, antifriction properties, corrosion resistance, and, when alloyed with Ni, high thermal and cryogenic resistance. The aim of this work is to investigate the structure and properties of hardfaced with CuAl8Ni2 aluminum bronze steel base. The main task is to observe the fatigue behavior in gigacycle range (>10^7 cycles to failure), to examine the fusion zone (absence of cracks, fusion mechanism, and mechanical properties). Also of interest is the study of structural changes in the recrystallization zone of the base steel metal and its mechanical properties.

Ultrasonic resonance fatigue testing at 20kHz is an appropriate method to test the fatigue properties in very high cycle fatigue (VHCF) domain beyond 10^7 cycles in a reasonable time.

It was found out that for a lot of steels there is no endurance limit in 10^6-10^7 range and specimens continue to fail after 10^7 even 10^8 cycles. Most of the fractures are initiated from internal defects or inclusions. So it can be stated that each fatigue failure mechanism have its own stress limit [6].

2.MATERIALS AND METHODS

2.1Ultrasonic fatigue testing

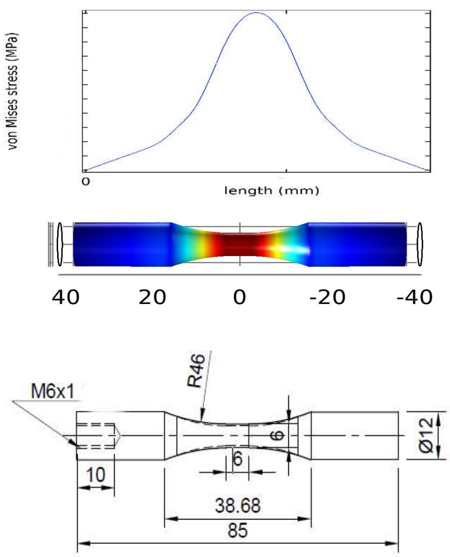
Fatigue tests were carried out by the ultrasonic fatigue machine, designed and assembled in Strength of Materials Laboratory Varna, Fig.1. The design principles follow the best practices, collected from C. Bathias in [7]. Since the only available commercial machine is Shimadzu's ultrasonic fatigue testing equipment (USF-2000A), which is presented in recent years, most of the laboratories in Europe had their own custom equipment designed, based on commercially available devices for ultrasonic welding.

For the assembly the MPI-Ultrasonics ultrasonic machine, generator, transducer and booster for ultrasonic welding, are used. The particular experiment is provided with conical sonotrode, designed by our team and machined in TU–Varna workshop. Monitoring, data acquisition and cooling systems are controlled by LabView routine.

All piezoelectric ultrasonic fatigue machines works in the same principle. To develop high stresses in the tested specimen, the ultrasonic fatigue testing requires cycle loading at its longitudinal resonance frequency 20±0.5kHz. The vibration of the specimen is induced by a piezoceramic transducer, which generates acoustical waves in the specimen through booster and sonotrode in order to obtain desired strain field from which the stresses are calculated based on the Hooke's law of linear elasticity. Specimen is a part of the ultrasonic resonance train, and unlike the standard fatigue test, the length and stress concentrator dimensions vary for each material. They shall be calculated after precise measurement of the material's dynamic Young's modulus and density.

The ultrasonic generator has phase locking loop control of the frequency in order to keep the resonance conditions and constant displacement amplitude. The specimens have one end free, and the load cycle is symmetrical (R=-1), Fig.2 A. Since the stress strain dependence is linear, the strains are controlled by measuring displacement amplitude at the free end of the specimen. It is monitored by fiberoptic displacement sensor (Philtec, Inc. Model D20).

A)



B)

Fig. 2 Design of the specimen. A) Amplitude stress distribution in resonance condition (~20kHz); B) Dimensions and hardfacing area

The fatigue test is conducted in pulse-pause mode with 3/1 ratio. In [8] results from various pulse durations show that the lifetimes are not dependent on the pulse duration, if proper ultrasonic load control is applied. Forced air cooling from the vortex tube was needed in order to keep the temperature below 30^{o}C. LabView routine is created in order to control pulse-pause times and monitor the displacement and temperature. The test is stopped when a crack develops, and the generator is unable to keep the resonance conditions. The final fracture of the specimens is done on tensile machine.

2.2 Material and specimen preparation

For the purpose of the study, test specimens of C45 steel were prepared, Fig.2,B. The blank is a calibrated rod with a diameter of ϕ12 in normalised condition (Re=275, Mpa, Rm=560Mpa according to the manifacturer's certificate). The stress concentrator is 38.68mm long. It has a cylindrical part with a length of 6mm and a diameter of ϕ6 and a total length of 38.68mm, completed with a radius R46. The total length of the sample L=85mm was obtained through FE eigenfrequency analysis in order to fit the first axial eigenshape, as a free body, to 20±0.5kHz. For this purpose, the dynamic modulus of elasticity was calculated on the blank. IET according to ASTM E1876 was used. A value of E=208GPa was obtained. The density of the material measured by water displacement method is similar to the theoretical value ρ= 7848kg/m^3. The samples were machined on a CNC lathe, with the profile of the concentrator, shown with a dashed line on Fig.2 B), followed by welding of aluminum bronze (CuAl8Ni2) by the TIG (tungsten electrode, inert gas) welding method, final turning to the final size, grinding and polishing. Upon checking, the resonant frequencies of the finished samples were obtained in the range of 20.1-20.2 kHz.

3. RESULTS

3.1. Fatigue testing results

The fatigue testing results are shown in Table 1. As it can be seen there are fatigue fractures beyond 10^7 cycles. The sample which reaches 10^8 cycles at fatigue loading 107MPa was considered as runout. As all the crack origins are subsurface at the fusion zone between hardfacing and base material, see 3.2. similar fatigue failure mechanism can be considered. To fit the experimental data in S-N field probabilistic model of Castillo-Canteli is used [9]. This model is based on Weibull distribution and creates a family of hyperbolic curves with a certain probability of failure. It is suitable for the low number of tested specimens. The horizontal asymptote of the curve is considered as endurance strength. The model is fit by ProFatigue software [10]. On Fig. 3 only the 50% probability curve is plotted. The endurance strength is estimated $\Delta\sigma_0$=74 MPa. For 10^8 cycles fatigue strength $\Delta\sigma$=143 MPa is calculated. Of course, due to low sample size credible interval (5-95%) is very broad and the results can be interpreted as indicative.

Table 1 Fatigue test results

Specimen Number	Alternating Stress Δσ, [Mpa]	Cycles to failure , Nf	Failure /Runout
1	206	5.62×10^3	F
2	190	1.2×10^6	F
3	176	1.56×10^7	F
4	144	1.8×10^7	F
5	107	1.1×10^8	R

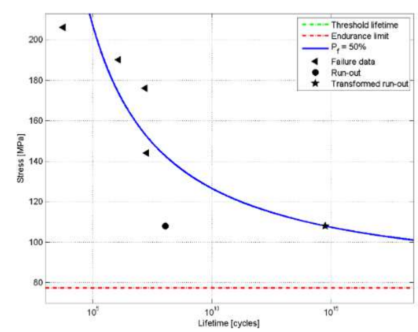


Fig. 3. Fatigue results in S-N field and P_f=50% curve (ProFatigue [10])

3.2. Fractographic Study

From the fractographic study conducted, characteristic zones are observed on the fracture surfaces of fatigue specimens. The examined fractures represent a bimetal of welded aluminum bronze on a base of steel C45. The focus of the fatigue crack (crack initiation site) and the area distribution between the fatigue zone and fast final fracture (overstress) zone, which depend on the magnitude of the fatigue loading [11] are of interest.

There are various fatigue loadings that can cause metal bond breakage and lead to failure. In this specific case, symmetric cyclic loading, using the tension-compression scheme was applied, creating an unfavorable loading pattern in the cross-section of the heterogeneous structure of the welded bimetallic samples. Hardfacing process forms a surface layer of metal with mechanical, chemical, and thermal properties fundamentally different from the base metal. The primary mechanism of plastic deformation in Cu is twinning and slip on the (111) system, while in steel Fe(α) it is slip on the (110) system. It is known that crack formation is a result of the increased dislocation density zone, influenced by the loading method, the plasticity of individual zones, the presence of chemical compounds in the metal structure (increasing deformation resistance), defects and metal imperfections in the structure, and stress zones in the cross-section. All the factors mentioned above influence the failure mechanism.

On figures 4, 5, 6, and 7, macrostructures of fractured surfaces, subjected to fractographic examination, are presented. The individual zones of fatigue fracture and final fast fracture are clearly distinguishable, as well as the focus of crack initiation and crack propagation direction. The fatigue loading used indicates that stresses are constant in the cross-section, without taking into account internal stresses, inherited from the welding process.

During classical hardfacing by arc welding, radial compressive stresses are primarily generated. Considering that Cu-alloys have high thermal conductivity and coefficient of thermal expansion, it is likely that after a rapid cooling of the deposited layer in the fusion zone, tensile stresses are formed. The configuration of the fatigue machine creates axial loading where stress alternates in axial direction.

The fatigue cracks in the test specimens occur due to sliding in the plastic zones of the welded and base metals, and the accumulation of dislocations in the brittle zone of the materials alloying. In this zone, precipitations of chemical compound δ-phase ($FeAl_3$) along the grain boundaries are observed. The accumulation of dislocations along the boundary of the fusion zone creates micro-zones of metal porosity (crack initiation focus), where intergranular cracking through the alloying zone occurs during tensile half of the fatigue loading cycle.

The examined specimen 1 (Fig. 4) clearly shows low-cycle fatigue fracture. This is evident from the cycles to failure data in Table 1. Fractographic studies of sample 1 in the fusion zone between the two metals show no delamination, but it is visible that crack origin is micro defect. The microstructure of the broken surface reveals a cellular fracture structure throughout the fracture section after failure due to low-cycle fatigue.

From the broken surface of specimen 2, shown on Figure.5, a high cycle fatigue (HCF) with a clearly defined fatigue zone and fast fracture zone is observed in the steel area of the bimetal. The mechanism of crack initiation is an

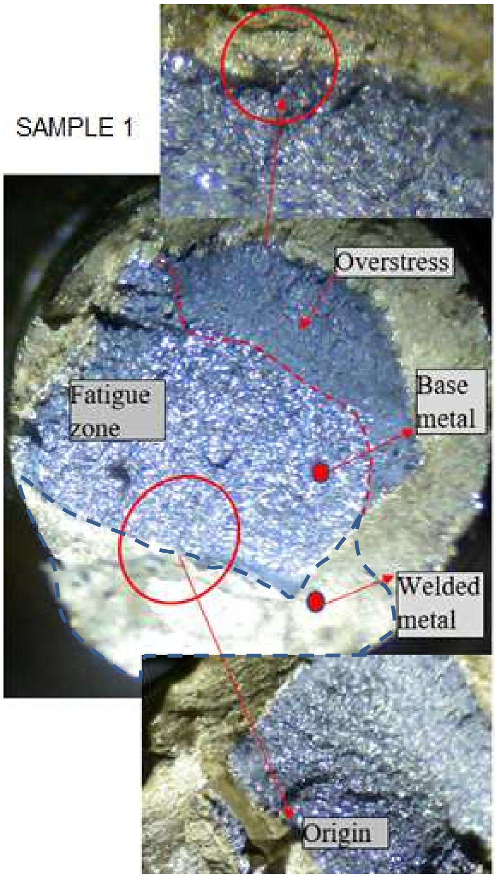


Fig. 4. Fatigue fracture surface of spesimen 1

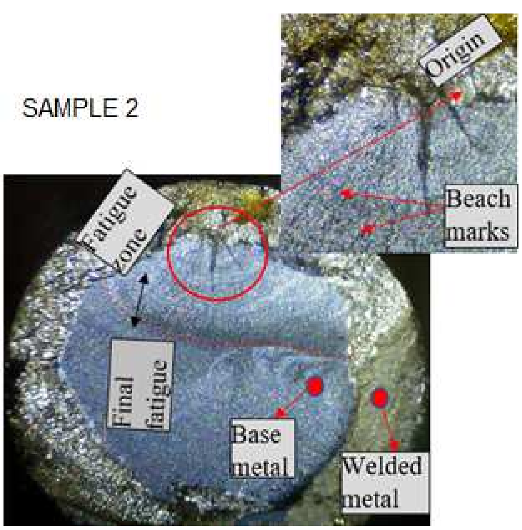


Fig. 5. Fatigue fracture surface of spesimen 2

increase in dislocation density in the plastic region up to the zone with increased hardness in the fusion zone. The accumulation of a large amount of energy along this boundary, due to significant amplitude of the stress cycle and the presence of a high dislocation density, leads to intergranular delamination.

Simultaneously, intrusion and extrusion processes occur in the fracture zone, manifested both radially (in the fracture) and tangentially through ongoing extrusion processes in the circumferentially welded copper alloy. In local areas (green color on fig.5) of the surface layer of the Cu alloy, in contact with the final fracture zone on the steel base, there is an axial cellular cracking. Between the two metals (in the fusion zone), no delamination or visible macro defects are observed.

Specimen 3, tested with an amplitude stress of 176 MPa, shows the fatigue fracture area significantly increased, becoming a function of the number of cycles over time. The mechanism of failure is the same as that of the previous specimen. It involves the crack initiation in the

fusion zone, intergranular fatigue crack development, and development of extrusion and intrusion mechanisms of sliding in the steel fracture zone. The macrostructure shows that the fatigue crack developed in a whirlwind shape with the crack initiation focus formed at its peak. In the contact zone of the fracture and the surrounding Cu alloy, the extrusion occurs with tangential spreading. Cellular fracture is observed in the contact zone between the steel and the Cu-alloy in the fast fracture zone (Fig. 6). The macrostructure does not indicate any delamination between the two metals or visible macro defects.

Specimen 4, shown on Fig. 7, tested at an amplitude stress 144 MPa, have a fatigue fracture area that occupies 85% of the sample's cross-section. The cracking mechanism is like the previous tests 2 and 3. The extrusion direction in the two bimetal constituents remains the same. In the base metal, circular propagation zones with a focus center are clearly outlined in the fracture zone, with the extrusion zones positioned perpendicularly to the circular zone and spreading V-shaped relative to the circular center. The highlighted area in blue represents cellular fracture. As the fatigue load amplitude decreases, the fatigue fracture area significantly increases, compared to the fracture depth, which is also related to the morphology of the fracture. Extrusion processes are observed in the zones of the base steel metal and the adjacent circumferentially welded metal at an angle to the deformation wave, allowing sliding along favorable crystallographic planes (systems). Cellular fracturing is observed in the fast fracture zone and in both metals (base and welded).

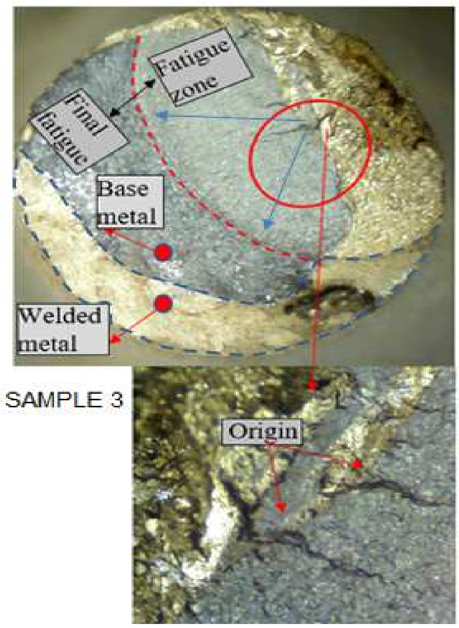


Fig. 6. Fatigue fracture surface of spesimen 2

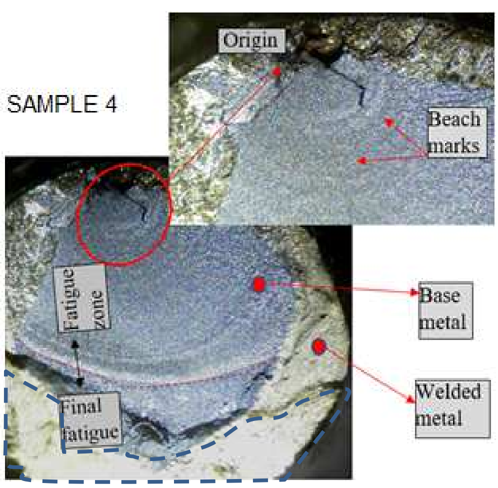


Fig. 7 Fatigue fracture surface of spesimen 4

3.3 Microstructural study

A microstructural analysis of the bimetal was conducted, using a dense round clamp to prevent rounding of the edges of the welded bronze metal, Fig.8. The phases in the fusion zone were primarily studied, where α-Fe+δ-phase ($FeAl_3$) is observed (Fig. 9).

In the depth of the bronze, single separations of δ-phase ($FeAl_3$) are observed. This is due to the high velosity diffusion processes that occur during the crystallization of the welded aluminum bronze. Characteristic twins are observed in the welded metal, Fig.10. In this zone, equiaxed crystals are observed, unlike the dendritic crystals that are characteristic of the welded metal zone.

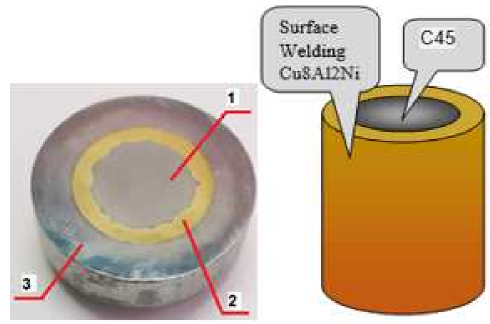


Fig. 8. Cross section specimen for microstructure analysis

1 - specimen base metal C45; 2 – specimen surface weld metal aluminum bronze; 3 - steel ring mount

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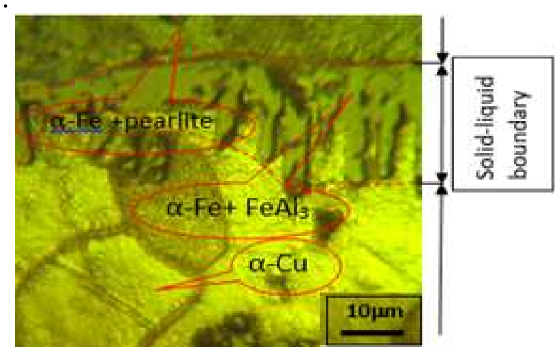

Fig. 9. Microstructure of hardfaced metal and fusion zone. Amplification X800

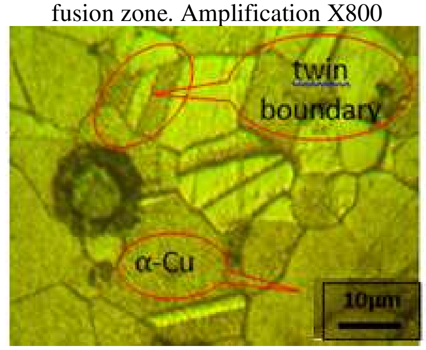

Fig. 10. Microstructure in welded metal. Amplification X800

3.4 Microhardness measurements (HV0.05)

All zones in the longitudinal direction from the welded metal, fusion zone of recrystallization, and base material have been studied. In the HAZ zone and the base metal, no significant peak values are observed. Grain coarsening is observed in the recrystallization zone. The values and hardness in the welded metal are close. Peak hardness values are observed in the fusion zone, which is likely due to the separated δ-phase, Fig.11, Fig.12

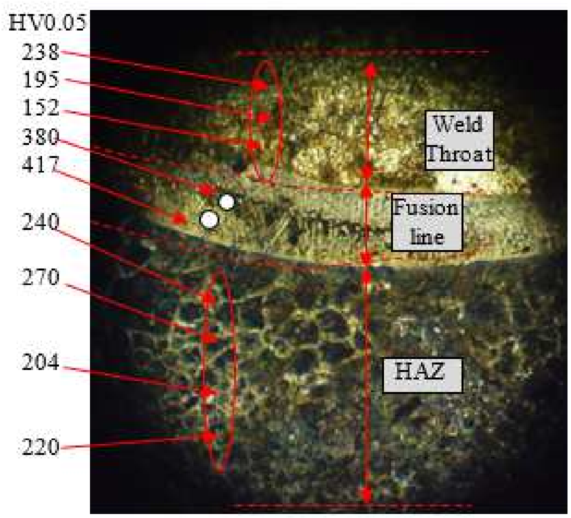

Fig. 11. Welded metal, fusion zone of recrystalusation. Amplification x100

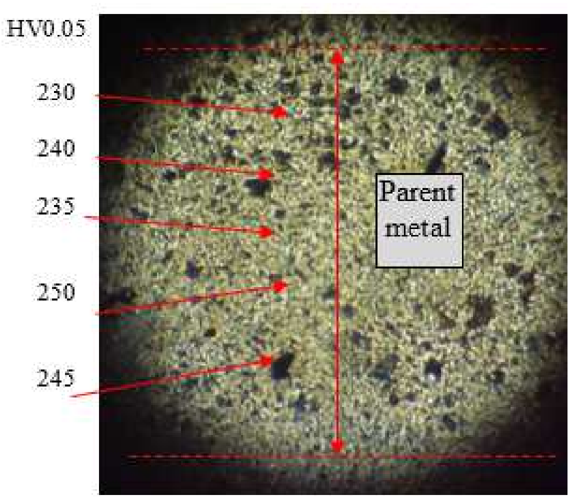

Fig. 12. Base metal zone. Amplification x100

4. CONCLUSION

Specimens for the ultrasonic resonance testing with hardfaced on the stress concentrator surfase, aluminium bronze are properly designed and mashined in order to meet the resonance conditon. The spesimens fail in VHSF domain beyond 10^7 cycles. In the examined fatigue fractures of the bimetal, the cracks originate in the fusion zone. With a decrease of the fatigue load, a proportional increase in the fatigue zone is observed, which is associated with a reciprocal increase in the number of cycles to failure. From the hardness measurements, it is established that the maximum hardness is in the fusion zone. In the HAZ zone, the hardness values are comparable to those of the base metal and the welded metal. Cracks are not observed in the individual zones of the bimetallic joint. In the zone of the welded metal, equiaxed grains are formed due to the chosen optimal welding regime.

5. ACKNOWLEDGEMENTS

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INITIATION ET CROISSANCE DE FISSURES SOUS CHARGEMENT CYCLIQUE DANS L'ACIER, RECHARGEMENT DUR AVEC BRONZE ALUMINIUM PAR METHODE DE SOUDAGE TIG

L'article présente une étude des propriétés de fatigue et de la microstructure de l'acier, rechargé avec CuAl8Ni2 (bronze d'aluminium). La méthode de soudage TIG est utilisée. Les éprouvettes revêtues sont en acier de construction C45. Certaines transformations structurelles ont été constatées dans la zone du métal ajouté, la zone de fusion et la zone affectée thermiquement (HAZ). La recherche comprend la détermination de la microdureté et des changements macrostructuraux dans des zones individuelles. Des essais de fatigue par résonance axiale sous cycle de chargement symétrique (R=-1) ont été réalisés, sur une machine de fatigue à ultrasons à 20 kHz, en observant l'initiation et la croissance des fissures dans le corps de l'éprouvette. Des études micro et macro structurales ont été réalisées dans la zone d'initiation des fissures.

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