Cavitation erosion damage of self-fluxing NiCrSiB hardfacings deposited by oxy-acetylene powder welding

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Abstract. This paper comparatively investigates the cavitation erosion damage of two self-fluxing NiCrSiB hardfacings deposited via the oxy-acetylene powder welding method. Examinations were conducted according to the procedure given by ASTM G32 standard. In order to research cavitation erosion (CE), the vibratory apparatus was employed. The cavitation damaged surfaces were inspected using a scanning electron microscope, optical microscope and surface profilometer. The hardness of the A-NiCrSiB hardfacing equals 908HV while that of C-NiCrSiB amounts to 399HV. The research showed that the CE resistance of C-NiCrSiB is higher than that of A-NiCrSiB. The results demonstrate that in the case of multiphase materials, like the NiCrSiB hardfacings, hardness cannot be the key factor for cavitation erosion damage estimation whereas it is strongly subjected to material microstructure. In order to qualitatively recognise the cavitation erosion damage of the NiCrSiB self-fluxing hardfacings at a given exposure time, the following factors should be respected: physical and mechanical properties, material microstructure and also material loss and eroded surface morphology, both stated at specific testing time. The general idea for the cavitation erosion damage estimation of the NiCrSiB oxy-acetylene welds was presented.

1. Introduction
Cavitation erosion (CE) is a very complex deterioration phenomenon. General, the CE phenomenon is summarised as a material degradation process involving harmful fluid behaviour started by pressure changes in the liquid. Once the liquid pressure drops, the vapour can grow, and as the pressure increases, the vapour bubbles implode. The resulting emission of liquid-jet and shock waves produces damage (cavitation erosion) to a solid material [1]. Though the CE damage origin has mainly the mechanical mode, it can be intensified by the corrosive environment of a working fluid, solid-particle action, elevated temperature environment or synergistic interactions between the deterioration processes of the listed machine parts is minimalised using different surface engineering processes. Thus, the broad range of methods, including induction hardening [2], thermal spraying [3,4], shot peening [5,6], ion-implantation [7,8], hard PVD films deposition [9,10], laser cladding and overlay welding [11,12], wet overlay welding [13,14], or surface alloying [15,16] are employed. Scientific papers report that the most popular materials for regenerating or prolonging the performance time of ferrous machine parts are metal alloys [17,18], polymers [19,20] and different types of composites [21,22]. In the case of metallic materials, nickel-based materials present a promising applicability to different types of metallic substrates [17]. The self-fluxing NiCrSiB and NiBSi alloys can be
deposited by various techniques, such as flame spraying [23,24], oxy-acetylene powder welding [25], laser cladding [26], plasma arc welding [17,27] and HVOF [28,29].

The self-fluxing nickel-based alloys have a multiphase microstructure consisting of nickel-based solid solution, chromium carbides, mainly Cr$_2$C$_6$ and Cr$_7$C$_3$, borides or complex chromium carboborides and eutectics e.g. Ni$_3$B, Ni$_5$Si$_3$ [25,28]. Furthermore, the hardness of deposits usually increases along with the percentage ratios of chromium, silicon, carbon and boron. Thus, nickel-based self-fluxing alloys are mainly used in fabrication of wear-resistant coatings operated in mining and oil-extracting, metallurgic, energy, stamping and pressing equipment, glass and chemical equipment, gas-pumping devices, automotive and boat parts, agricultural technology, etc. Generally, the studies on the CE behaviour of the NiCrSiB hardfacings are scant. Moreover, the diversity of deposition techniques and a variety of chemical compositions of nickel self-fluxing alloys make it difficult to classify their CE resistance. Thus, there is a need to investigate the CE process of the NiCrSiB deposits. In order to fully understand the CE mechanism, the relationship between hardness, microstructure and surface roughness damage should be clarified [30] too.

This conference paper aims to discuss the factors influencing the damage due to cavitation erosion of the NiCrSiB powder welds.

2. Materials and methods

Two NiCrSiB hardfacings were deposited by oxy-acetylene powder welding on ferrous substrate grade EN-GJL-200 (grey cast iron). The details regarding the welding procedure are presented in a previous paper [30]. Deposits differ in chemical composition, microstructure and hardness – see Table 1. The microstructure was studied in polished metallographic samples using SEM (scanning electron microscope). The hardness of powder welds was estimated using a Future-Tech FM800 hardness tester according to the ISO PN-EN 6507 standard. Prior cavitation erosion (CE) testing samples were machined to achieve the diameter of $\varnothing 25$, the height of 10 mm and mirror polished surface roughness of $S_r<0.06$ $\mu$m and $S_z<0.72$ $\mu$m.

The cavitation erosion (CE) tests were conducted in accordance with the ASTM G32 standard recommendations using vibratory apparatus and the stationary specimen method. The scheme of the test device is presented in Figure 1. In order to conduct tests, the mirror-polished hardfacing surface was positioned at 0.05 mm from the vibrating horn tip. Total cavitation time equalled six hours. The samples were weighed using an analytical balance with an accuracy of 0.1 mg. The mass loss of the tested NiCrSiB hardfacings was presented as a function of the exposure time. During the stated CE time intervals, the eroded surfaces were investigated using a Nikon SMZ 1500 stereo optical microscope (OM) and scanning electron microscope (SEM, Phenom World, USA). Finally, the damaged surfaces were measured using a roughness profilometer. The 2D roughness profiles and 3D surface morphology were determined by means of T8000RC 120–140 profilometer (Hommel–Etamic) according to ISO 4287 and ISO 25178 standards, respectively [30].

Table 1. Chemical composition of materials used for oxy-acetylene powder welds and nominal powder welds hardness according to the manufacturer’s datasheet [31].

| Specimen name | Chemical composition of the materials, wt% | Hardness, HRC |
|---------------|-------------------------------------------|---------------|
|               | Ni | Cr | Si | B  | C  | Fe | Other          |               |
| **A-NiCrSiB** | Balance | 17.0 | 4.5 | 3.6 | 0.6 | 3.0 | Mo 2.5; Cu 2.5 | 53-63          |
| **C-NiCrSiB** | Balance | 7.5 | 3.5 | 1.7 | 0.25 | 2.5 | -              | 38-45          |
3. Results and discussion

3.1. Microstructure and hardness of the NiCrSiB powder welds

On the basis of the results of metallographic investigations performed using SEM, hardness analysis and analysis of the cavitation erosion (CE) plots followed by the surface profilometric measurements confirm the influence of hardfacings microstructure on the cavitation erosion behaviour. The microscopic investigation confirms the reference information regarding the microstructure of the hardfacings [25,32]. The microstructures of oxy-acetylene deposits consist of a relatively ductile nickel-based matrix with different amounts of hard phases (Figure 2). The A-NiCrSiB sample contains a much higher percentage ratio of hard particles than the C-NiCrSiB hardfacing (table 1), which comes from the chemical composition of feedstock metallic powders. Furthermore, in the case of the A-NiCrSiB sample, hard phases are visible in the form of particle clusters and agglomerates.

Figure 1. Representation of the ultrasonic vibratory test rig used for cavitation erosion testing (according to the stationary specimen configuration and standard procedure).

Figure 2. Microstructures of the nickel-based hardfacings, SEM.
The microstructure strongly affects the hardness scattering, visible in Fig. 3. The mean hardness of the A-NiCrSiB hardfacing (908 HV 0.05) exceeds those given for C-NiCrSiB (399 HV 0.05) twice. Both microstructure and hardness are important factors for the erosive performance of metal alloys.

3.2. Cavitation erosion performance of the NiCrSiB hardfacings

The analysis of CE results (Fig. 4) indicates that A-NiCrSiB displays higher material loss than softer C-NiCrSiB. Figures 5 and Figure 6 show the differences in the morphologies of the eroded surfaces. The comparative investigation of the hardness and time-dependent erosion material loss, given in the previous study [30], acknowledges the general influence of hardness and microstructure on material loss and CE behaviour.

![Figure 3. The Vickers hardness (HV0.05) of the NiCrSiB hardfacings [30].](image1)

![Figure 4. Cumulative mass loss of the NiCrSiB powder weld hardfacings [30].](image2)

![Figure 5. The surfaces of the NiCrSiB hardfacings damaged due to cavitation erosion after 6h of exposure to cavitation, optical microscope.](image3)
Figure 6. Cavitation eroded surfaces of the NiCrSiB hardfacings observed at 6h of testing, SEM.

Moreover, it is believed that surface roughness is the main indicator of metallic surface layer industrial usability [33–35]. Therefore, as in the example of the many different deterioration processes, the CE rate can be stated by surface roughness changes evaluation. This was discussed in previous papers regarding ceramic coatings [36], composites [37], plastics [19] and metallic materials [38]. Thus, the CE damage of the NiCrSiB hardfacings was evaluated by the surface profilometer measurements, see figure 7.

Figure 7. Roughness profiles of self-fluxing hardfacings evaluated at 6h of cavitation erosion testing.
The analysis of the results given in Fig. 7 allows stating that the morphology and roughness parameters of the eroded surfaces supplement the erosion behaviour. According to the previously published roughness results [30], the A-NiCrSiB specimen presents higher $S_4$ and lower $S_u$ roughness parameters than the C-NiCrSiB specimen that has a relatively homogenous microstructure. Selective phases removal and low surface plastic deformation result in the growth of cavitation pits observed for A-NiCrSiB, while for the C-NiCrSiB hardfacing, the softer matrix undergoes uniform deformation of the surface and minimal pitting, visible in roughness profiles given in Figure 7.

3.3. The cavitation erosion damage ($CE_d$)

The literature survey shows various attempts for assessing the CE resistance of different materials [39–42]. Nevertheless, there is no report for the formula given for the NiCrSiB hardfacings. The analysis of the findings given in the current and previous paper [30] allow proposing the general qualitative relationship which can be used for estimating the cavitation erosion damage ($CE_d$) of a selected group of metallic materials, shown by the formula (1).

$$CE_d(t) = f(M,P,S,L)$$

where: (M) – material microstructure factor; chemical composition, number of phases, phase morphology, structure refinement and homogeneity, porosity, etc; (P) – physical and mechanical properties: represented by hardness, plasticity, Young’s modulus, cohesion, toughness, thermal conductivity, corrosivity etc; (S) – surface morphology at specific test time: characterised by surface roughness, surface development rate, nonuniformities, etc; (L) – material loss assessed at specific cavitation exposure time – mass loss, volume loss, erosion rate, etc.

The proposed $CE_d$ qualitative relationship combines the crucial input factors such as M and P integrated with the other indicators assessed at specific testing times, namely S and L. It seems clear that in order to select the scalar value, the $CE_d$ must be verified for a broader range of NiCrSiB hardfacings. Universally, hardness is known as a predominant material feature utilised for the measuring of the material resistance to cavitation erosion deterioration. Though, this study performed for the NiCrSiB powder deposits shows that the ratio of cavitation erosion loss depends on both microstructure and hardness and these factors should be considered together. It seems that in the case of complex-microstructure materials, including the NiCrSiB hardfacings, $CE_d$ depends very strongly on microstructural uniformity. Furthermore, to predict the CE failure of specific materials, their in-process damage behaviour should be taken into account. Thus, not only mass loss but also the development of surface morphology should be involved. Each of the factors given in a proposed $CE_d$ relationship should be selected with care and this formula will be validated for the set of self-fluxing NiCrSiB hardfacings [30] to obtain specific scalar values.

4. Conclusions

This study aimed to examine the factors influencing the damage due to cavitation erosion of the NiCrSiB hardfacings deposited via the oxy-acetylene powder welding method. The general idea for the cavitation erosion damage ($CE_d$) estimation of NiCrSiB oxy-acetylene welds was presented. The analysis of the results leads to the following findings:

- The NiCrSiB oxy-acetylene powder weld microstructure consists of nickel rich matrix, hard phases and eutectics and. The microstructure of hardfacings influences the hardness and CE mechanism. The average hardness of A-NiCrSiB, was 908 HV and those reported for C-NiCrSiB was 399 HV.
- The study showed that the cavitation erosion resistance, expressed by the cumulative mass loss, is lower for A-NiCrSiB than for the C-NiCrSiB hardfacing. The C-NiCrSiB powder weld has lower hardness and a lower rate of damage than harder A-NiCrSiB alloy.
Results demonstrate that for multiphase structured materials, including the NiCrSiB hardfacings, hardness cannot be the key indicator for cavitation erosion damage (CE$_d$) estimation. Cavitation erosion resistance is strongly dependent on the material microstructure.

In order to qualitatively evaluate the CE$_d$ of the NiCrSiB self-fluxing hardfacings at a given exposure time, the following factors should be taken into account: physical and mechanical properties, material microstructure and also material loss and eroded surface morphology, both stated at specific testing time.

5. References

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