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SURFACE REMELTING OF MULTI-PHASE SINTERED STEEL

This study presents the results of the investigations of the effect of surface remelting using arc welding (GTAW) on the microstructure and selected properties of surface layer of sintered steels 304L and 434L. It was found that in order to improve surface quality in these sinters, remelting should be carried out at lower current intensities, i.e. 30A and 40A. The surface treatment carried out in the study allowed for obtaining an uniform cellular-dendritic microstructure in surface layer. X-ray examinations demonstrated the effect of compressive stress in surface layer, which reduces the risk of cracking on the surface.

Keywords: *sintered stainless steel, arc surface remelting*

1. Introduction

Among the group of corrosion-resistant steels, duplex steels are characterized by particularly good combination of the properties typical of chromium ferritic steels and chromium-nickel austenitic steels. They exhibit high mechanical strength, elasticity, weldability and very high corrosion resistance and oxidation in different environments and operating conditions. However, manufacturing of two-phase steels using conventional methods is complicated from the technological standpoint and thus expensive [1, 2]. Recent years have seen a dramatic increase in interest in alternative methods of manufacturing of these steels, offered by powdered metallurgy. This technology allows for large-scale production of components with complex shapes, ensuring high precision of dimensions and surface quality even for small parts [3]. Manufacturing duplex steel by means of powder metallurgy is carried out through sintering of the mixture of alloy powders with chemical composition corresponding to duplex steel, mixture of ferritic and austenitic steels and the mixture of ferritic, austenitic or martensitic steel with the elements which destabilize the resultant phase, which allows for creation of the two-phase structure [4]. Moreover, powder metallurgy uses 97% of burden material, which makes it a nearly waste-free technology, thus more economical and ecological compared to conventional procedures. The technology also allows stainless steels to be used in control devices, household equipment, medicine, tools as well as in aviation and automotive industries which are the recipients of over 70% of sintered products [5].

A major limiting factor in broader use of sintered austenitic-ferritic steels is its worse mechanical and corrosion properties compared to their cast counterparts. This is caused by the presence of porosity. Although powder metallurgy allows for precise determination of chemical composition of sinters and controlling the conditions of sintering, limitation of porosity is possible only to some extent [2, 6]. Presence of empty holes in the material might generate cracking during the use of these materials, whereas porosity adversely affects corrosion resistance as it increases the surface area of the material which is exposed to direct contact with corrosion environments [7÷9]. Given that sintered duplex steels are typically designed for using in automotive industry, e.g. exhaustion systems elements which operate under corrosion conditions, the authors of the present study focused on the improvement in the properties of surface layer.

Recent two decades have seen an increasing interest in surface remelting. Previous scientific output in this field provides evidence that surface remelting in sintered stainless steels using concentrated heat sources favourably affects the improvement in functional properties of these materials [10÷12]. A particular popularity has been observed in application of laser techniques. They are characterized by high precision, while a stable and focused laser beam, coupled with dynamic cooling, allows for obtaining the remelted layers with the fine-crystalline structure [13÷15, 18]. The obtained surface layer is characterized by insignificant surface roughness and total reduction in open porosity, i.e. the places which are conducive for creation of corrosion nuclei [16]. Moreover, remelting of sintered alloy steels is a particularly justified surface treatment since it does not affect the chemical composition of the material [17]. It can be expected that the properties of the sinter that result from chemical composition and sintering parameters will not deteriorate. Laser remelting offers a range of benefits. However, from the economic standpoint, this process is very expensive. The present study proposes the use of a cheaper but relatively effective TIG (GTAW) method. The opportunities of monitoring of a number of parame-

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ters e.g. current type and intensity, arc voltage, surface scanning rate and selection of the electrode material/diameter make it easier to control the quality and properties of the modified surface layer. The arc method might be considered as an alternative solution to the laser technologies. Using TIG devices, the remelted layers with the structure and properties similar to the laser-modified layers are obtained [18÷21].

The study presents the results of the investigations of the effect of remelting by means of GTAW method on the microstructure and selected properties of surface layer in sintered multi-phase steel, obtained from the mixture of powders of austenitic and ferritic steel.

2. Research material and methodology

The examinations were carried out for the specimens of sinters of stainless steel powders (304L and 434L), manufactured by Hoganas AB (Sweden). The mixture of powders was prepared using the following proportions: 20% 304L: 80% 434L (marked as 20A-80F). The specimens were compressed with pressure of 720 MPa and sintered at temperature of 1250 °C for 30 minutes in the atmosphere of dissociated ammonia (75% H_2: 25% N_2) and cooled at cooling rate of 0.5 °C/s. Table 1 presents chemical compositions of individual powders.

Density of the sinters amounted to 6.96 g/cm^3. Porosity was determined by means of microstructural examinations and software for computer image analysis. The porosity on the surface and in the cross-section amounted to 3.06 ± 0.7% and 2.68 ± 0.4%, respectively. The sinter showed the multiphase microstructure with the presence of austenite, ferrite and martensite (Fig. 1).

The diagram of the GTAW method and the dimensions of the remelted specimens are presented in Fig. 2. Table 2 presents the parameters of remelting operations.

Parameters of arc remelting of sinter 20A-80F Table 2.

No.	Current Intensity I [A]	Arc Voltage [V]	Total Arc Power qc [W]	Linear Energy E [kJ/m]	Scan Rate V [mm/min]	Type and Flow Pattern of the Inert Gas
1.	30	10	300	39.47	460	Argon ~10 l/min
2.	40	10.5	420	35.92		
3.	50	10	500	42.76		
4.	60	10.5	630	53.88		

The effect of remelting on the quality and microstructure of surface layer was evaluated based on microscope observations of the remelted surface and metallographic sections. Geometry of the remelted zone (depth and width of remelting) was also determined.

Chemical composition of sinter 20A-80F and steel powders 304L and 434L [wt%] Table 1.

Powder	Cr	C	Ni	Si	Mn	Mo	N	O	S	Fe
304L(A)	18.9	0.013	11.2	0.9	0.1	–	0.02	0.28	0.005	rest
434L(F)	16.2	0.015	–	0.8	0.1	0.98	–	–	–	rest
20A-80F	16.74	0.015	2.24	0.82	0.1	0.78	0.004	0.056	0.001	rest

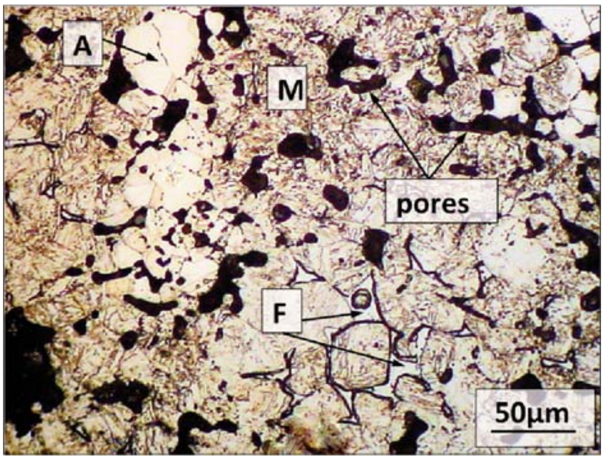

Fig. 1 Microstructure of 20A-80F sinter, magnification 200x

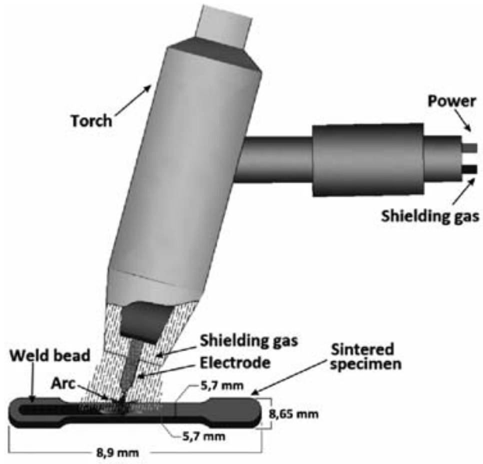

Fig. 2 Surface remelting using GTAW method

Furthermore, the authors evaluated surface topography and measured roughness parameters for each sample by means of profilometer Hommel T1000. The measurements were carried out in contact with the examined surface through coupling of the indenter with differential measurement system.

Parameters of stress measurement by means of $\sin^2\psi$ method Table 3.

Angle 2θ	59.9°
(hkl)	(022)
Peak Slope	0; 24.095; 35.264; 45.00°
Young's Modulus	$220*10^3$ MPa
Poisson's Ratio	0.28
X-Ray Lamp	Co; λ_{Co} = 0.17902 nm

The state of residual stresses in surface layer was determined by an X-ray method ($\sin^2\psi$) using Seifert XRD-3003 diffractometer. Dedicated software (Rayflex-Stress Analyzer) was used for determination of angular positions of diffraction peaks from austenitic phase. The parameters of the measurement are presented in Tab. 3.

Microhardness tests in remelted zone and the adjacent zones were carried out using Vickers method with the load of 490 mN by means of microhardness tester Future- Tech FM-7.

3. Discussion

The density of the modified sinter of 6.96 g/cm^3 suggests that remelting might have caused shrinkage due to a local change in volume. This phenomenon is unfavourable as it generates stress in surface layer and cracking of the surface [22, 23]. Using the arc method (GTAW) allows for limitation of the volume of liquid in the remelted zone through opportunities of monitoring of a number of process parameters. Application of different current intensities led consequently to obtaining remelted layers with varied surface geometry. Figures 3 and 4 present macroscopic effects of selected variants of the treatment used. The best surface quality was found for the specimens remelted with current intensity of 30 A and 40A. Presence of small areas of scales was found on the surface, which was easily removed through polishing. Heat impact zone was characterized by a colourful deposit formed by a thickening of the natural oxide layer. The open porosity was totally eliminated. Current intensities of 50 A and 60 A were too high and numerous fusions were observed on the surface of the sinter. Higher current intensity affected surface geometry in the specimens unfavourably as it was characterized in both cases by considerable waviness. The results of profilometric examinations revealed that application of current intensity of 30 A reduces the roughness in the sinters studied. As results from Table 4 and Fig. 5, the value of Ra parameter increases after arc remelting at current intensity of 40 A to 0.26 μm compared to the initial state. The values of roughness parameters for the surface of the specimen remelted using 60 A

Comparison of roughness parameters for remelted surface and input material Table 4.

Roughness parameter	Substrate material	30A	40A	50A	60A
Ra	2.99	2.27	3.25	9.14	25.96
Rz	31.03	17.32	23.80	64.71	113.42
Rmax	48.74	23.91	27.81	106.65	145.47

R_a – arithmetic mean roughness deviation from mean line,
R_z – maximum height of the profile,
R_{max} – maximum distance of profile peak from the lowest valley.

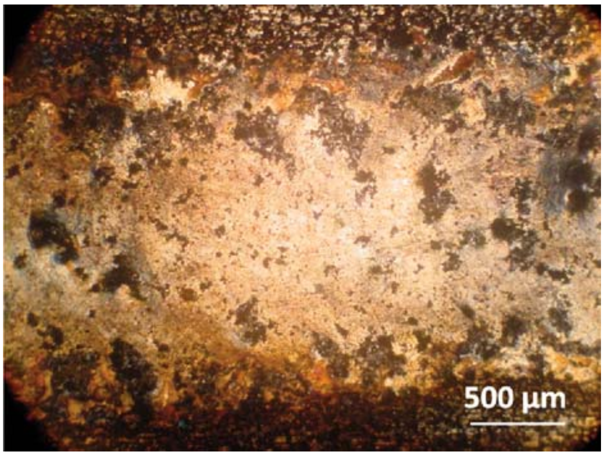

Fig. 3 Macroscopic effects of remelting sinters 20A-80F at current intensity of 40A

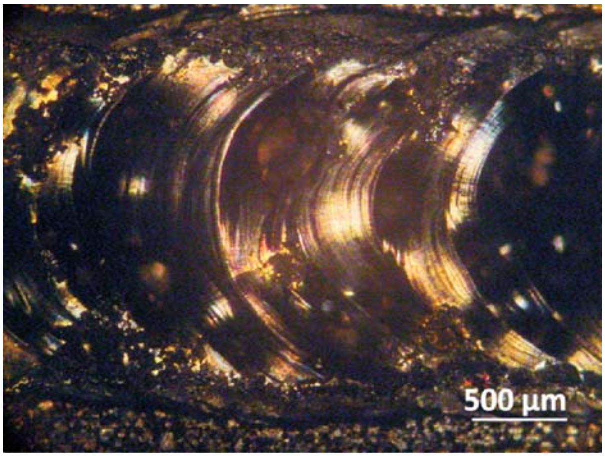

Fig. 4 Macroscopic effects of remelting sinters 20A-80F at current intensity of 50A

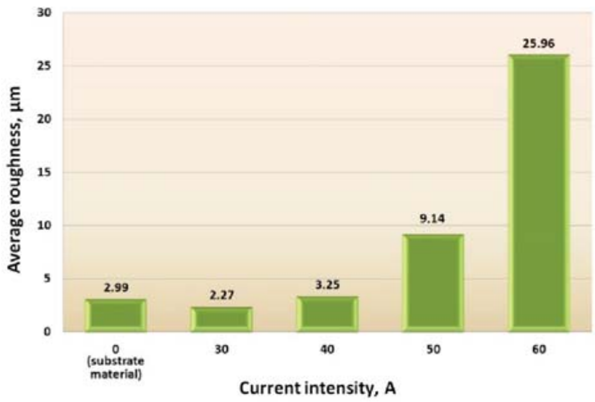

Fig. 5 Ra parameter vs. current intensity

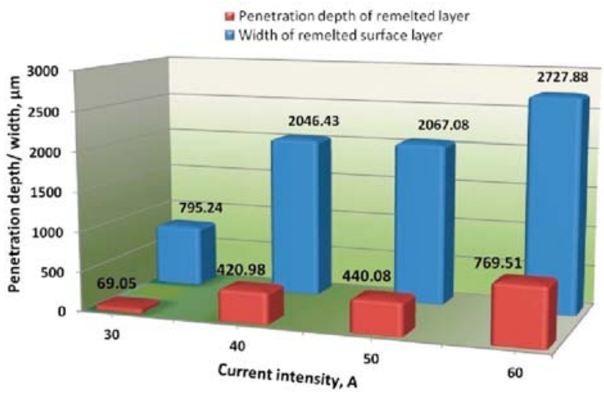

Fig. 6 Geometry of remelted layers vs. current intensity

current intensity exceeded the measurement error of the profilometer, which causes that the recorded data might contain errors.

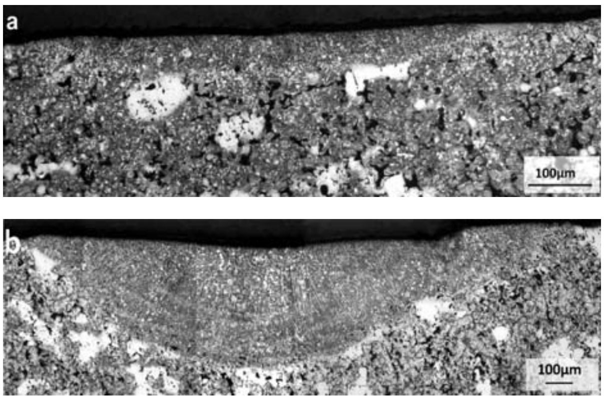

Fig. 7 Microstructures of surface layer of the sinter after remelting at the current intensities: a) 30 A, b) 40 A

Macroscopic examinations were employed to determine the width and depth of remelted layers. The results of the measurements were presented in the form of the chart (Fig. 6). Both parameters which characterize the geometry of surface layer are directly proportional to the value of current intensity. The highest depth of remelting and the widest path (769.5 µm and 2727.88 µm, respectively) was obtained after remelting with current intensity of 60 A. For intensities of 40 A and 50 A, the obtained remelted layers have similar geometry, whereas in the case of the treatment with current intensity of 30 A, changes were found in the insignificant volume of material.

Figures 7a and 7b present microstructures of surface layers after remelting with current intensities of 30 A and 40 A. Examinations by means of optical microscope revealed a primary character of microstructures for the obtained remelted layers. Using the formula (1) based on chemical constitution of the sinter; the authors calculated the ratio of Cr and Ni equivalents. The obtained value amounts to 6.84, which points to a ferritic character of solidification [24].

$$\frac{R_{Cr}}{R_{Ni}} = \frac{Cr + Mo + 1.5Si + 0.5Nb}{Ni + 30C + 0.5Mn} \qquad (1)$$

Ferrite was formed during cooling, between dendritic grains of austenite. Furthermore, the authors found that ferrite fraction is the lowest in the layer remelted with current intensity of 60 A. This might be caused by the fact that in the case of higher linear energy or arc, solidification and cooling rates are lower, which allows dendritic cells to grow and take more volume of the material. Therefore, the column grains were observed mainly in the areas located at the contact with substrate (Fig. 8), whereas on the surface, where the heat is transferred much faster, a fine grain structure was formed.

Figure 10 presents a microhardness profile for surface layer of the sinter after remelting. The highest hardness in remelting zone was observed for the sinter remelted with current intensity of 60 A. The surface treatment caused that the microstructure of surface layer was homogenous, which was suggested by similar values during measurements performed in the remelting zone for individual cases. A considerable dispersion of the values of microhardness results from non-homogenous microstructure of the sinter which in its input state contains martensite, ferrite and austenite (Fig. 1). Microscopic examinations did not reveal a distinct transient zone between the remelted material and the core. However, a decline in microhardness was found in all the cases in the remelted zone near the substrate. Unequivocal explanation of this phenomenon is yet to be researched.

Table 5 presents fundamental parameters and results of stress measurements in remelted surface layers. Figure 9 shows diffraction peaks depending on the variable slope ψ with the example of a specimen remelted with current intensity of 30 A. Since the level of residual stress considerably affects strength properties of the material, it seems beneficial to generate compressive stress in the remelted layer, which might reduce the risk of cracking. The mea-

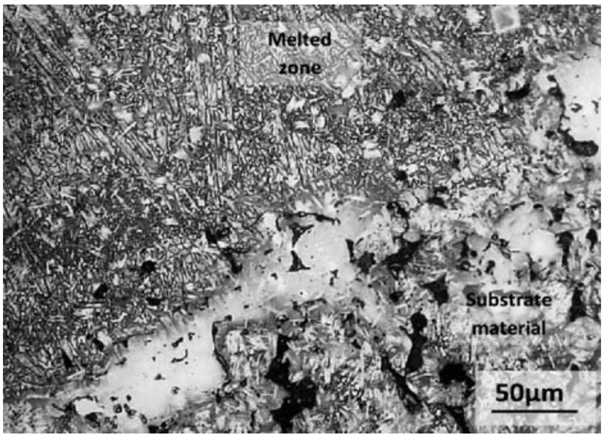

Fig. 8 Microstructure of remelted layer near substrate material (I = 40 A)

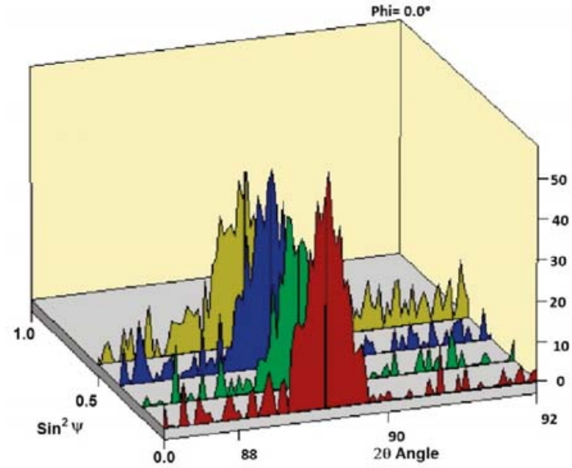

Fig. 9 3D diffraction peaks for variable slope ψ

surements demonstrated that compressive stress is generated in the remelted areas analysed in the study.

Stress in remelted surface layers Table 5.

Current Intensity I, A	Stress for 2θ = 59.9	
	σ	τ
30	778.4	769.2
40	734.3	−688.0
50	963.0	−298.1
60	81.7	−357.9

4. Conclusions

The results of the investigations focused on the evaluation of the effect of surface remelting on the microstructure and selected properties of surface layer of multi-phase sinter 20A-80F lead to the following conclusions:

- Application of arc method (GTAW) allowed for formation of a fine grain cellular-dendritic microstructure in surface layer.
- Both width and depth of remelting are directly proportional to the values of the used current intensity. The highest values of these parameters (2727.88 μm and 769.5 μm, respectively) were obtained after remelting at current intensity of 60 A,
- Remelting of the surface of the sinter 20A-80F at the current intensity of 30 A and 40 A allowed for elimination of open poros-

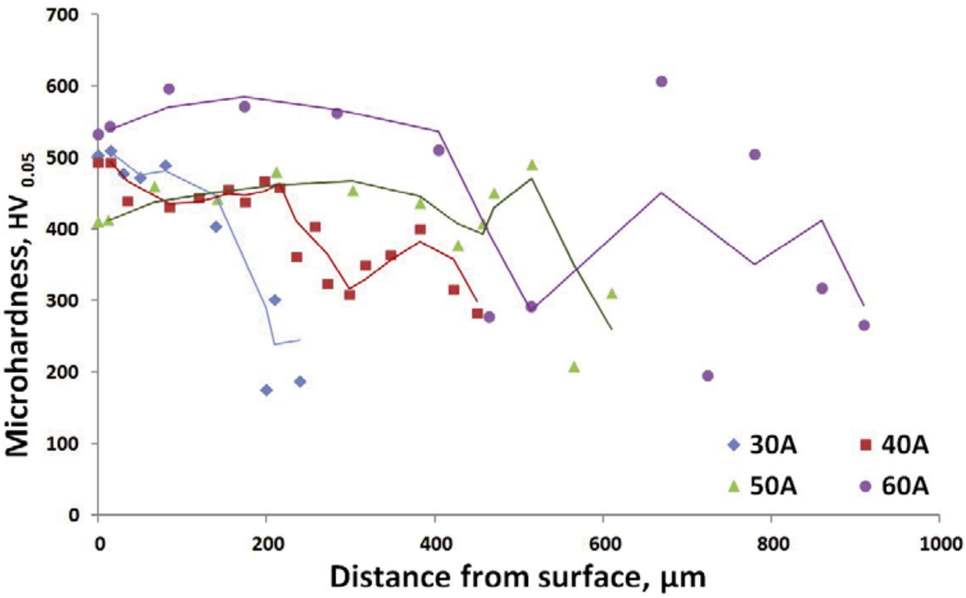

Fig. 10 Distribution of Vickers microhardness in surface layer of the sinter 20A-80F after remelting with different current intensities

ity and reduction of roughness. Sinter surface after remelting with current intensity of 50 A and 60 A was characterized by considerable waviness and presence of fusions,
- Compression stress was present in the obtained remelted layers
- The highest microhardness in the remelted layers was obtained after remelting with current intensity of 60 A
- Optimum current intensity used during remelting of multi-phase sinters studied amounted to 40 A. The obtained surface layer had suitable depth and width and was characterized by good quality and insignificant surface roughness.

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