STRUCTURAL DEGRADATION OF HETEROGENEOUS WELDED JOINTS

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Resume

Developing the techniques of welding materials with higher dynamic strength onto the rolling surfaces of rails is one of the options for increasing their operational endurance. The subject of this paper is an analysis of heterogeneous weld joints experimentally manufactured by welding medium-carbon austenitic steels onto high-carbon unalloyed pearlitic steels. The analyses focus on examinations of the marginal mixing of the materials at the fusion line and the circumstances under which intercrystalline cracks form in the weld deposit layers. Structural analyses, chemical microanalyses and a hardness assessment were performed in order to identify the corresponding structural changes. The proportion of zonal vs. interdendritic segregation of the alloying elements in the degradation of the welded joint was distinguished. We described the nature of the structural heterogeneities produced, locally connected with the martensitic transformation. The chemical heterogeneity leading to the formation of martensite at grain boundaries was identified as the limiting effect.

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1. Introduction

Weld surfacing is widely used for maintenance and repair of railway profiles. It is also the technique of depositing a layer of material onto the contact surface to make it more resistant to wear. Welding materials with a higher operational endurance onto the most exposed portions of the tram rails is one of the ways of extending their service life. Selected portions of the rolling surfaces of the rail profiles are modified by milling in slots, which are then overlaid with welded material with the required properties. They are then ground to the prescribed shape. This brings considerable advantages concerning the possibilities for producing welded joints. Overlaying welding in a workshop environment provides substantially more stable welding conditions. Development of these techniques therefore allows a much wider range of options of applicable filler materials and variable work techniques compared to standard repair techniques.

Overlay welding materials are used depending on the specific conditions or operational requirements. The operational load in the wheel/rail contact system is of a specific nature. It is a combination of stress where contact fatigue and adhesion dominate with a share of abrasion wear. The service behavior and safety of the railway profiles is influenced not only by an initial strength and toughness. The typical fatigue defects, squats and head checking, occur in heavily deformed microstructure, while ductility is exhausted. Required ability to consume some energy through plastic deformation in the process of crack propagation means high fracture toughness. There is a mutual competitive relationship between just initiated fatigue cracks and rail contact surface wear rates. The relationship between wear rate and growth rate of crack tip is the most important parameter of maintenance [1]. The abrasion and adhesive wear processes in the wheel-to-rail contact are of critical importance to the development of new material and scheduling maintenance operations, such as grinding rail sections. To predict tribological processes, wear tests have to be performed under various predefined parameters and different rail material combinations [2, 3]. The fatigue defects are formed more likely, when the adhesion limit decreases due to the presence of water. It is important to identify the environmental conditions where adhesion can be maintained for reducing the likelihood of crack initiation [4].

As concerns material parameters, the requirement is therefore for high fatigue resistance, dynamic yield point, and resistance to adhesion and abrasion wear. In terms of material criteria, the requirement for safe operation is reflected in the demands for the material parameters pursuant to fracture mechanics.

Standard pearlitic steels with higher initial strength are produced by lowering interlamellar distance after heat treatment, in direct proportion to increased carbon content. Initial crack growth was found along favourably aligned and strained prior-austenite grain boundaries, particularly if the boundary contains pro-eutectoid ferrite [5, 6].

Each austenitic steels, used for surfacing, exhibit a different hardenability and evolution of the microstructure with plastic strain. For example unhardened Hadfield steel, which is widely used for highly loaded parts of railway way, exhibits a high toughness performance, whereas fatigue and abrasion are the marked wear-producing mechanisms at the loaded layers. High strain-hardening was discovered with absence of martensite transformation, only by occurrence of mechanical twinning [7].

Successful surfacing requires an optimization of the process parameters to secure low dilution and crack-free layers. This needs a thorough understanding of the process affecting the technological and metallurgical characteristics of the overlays. Controlling the dilution by measuring the weld bead geometry is used for a effectively selecting the process parameters to achieve the desired quality of the overlay [8]. It is essential for particular weld parameters, materials and weld geometry to evaluate influence of each sources of chemical heterogeneity and a damage of the overlay material.

The proportion of the stress components depends on the operating conditions and differs in the various portions of the track superstructure and rail profile. The overlaying welding techniques discussed are applicable as a method to extend the service life of the most exposed segments, especially bends and frogs in rail crossings.

2. Research focus

The quoted demands on the weld deposit materials (contradictory to some extent) lead towards the application of austenitic steels with a medium carbon content. The base material, i.e., standard rail materials, is pearlitic steel between 0.5 and 0.7 % C in the strength range based on the carbon content. The welded joints are therefore both chemically and structurally heterogeneous interfaces with increased requirements on both the welding technique and joint quality, which is the chief drawback of the discussed overlaying welding techniques. The fusion line between high-carbon unalloyed steel and a high-alloy austenitic steel produces specific problems. Defects of welded joints that occur in the field are caused by a very wide range of degradation mechanisms [9, 10, 11]. The standard requirement for implementation of a newly developed technique of this type is the verification of the possibility of repair overlays on rail profiles modified in this way. Therefore, the technological development process has included verification of limits:

- when overlaying welding has limited conditions for preheat (here, up to 110 °C);

- when the weld deposit has to be repaired (due to wear) outside the originally welded profile.

The limit conditions of heat input for the formation of carbides along the grain boundaries in austenitic steels were tested. The works presented below studied the limit degrees of chemical heterogeneity of the intermediate layers. The purpose of the analyses was experimental research into processes that are limiting for specific applications and material combinations.

3. Experiment description

The technique in question was tested on a series of experimental weld deposits on the tram track crossing block. Due to the favourable combination of resistance to dynamic loading with an excellent resistance to both adhesion and abrasion, we proposed the weld deposit to be made using an austenitic material with a medium carbon content - SK AP-O filled Cr-Mn based wire (1.6 mm). An austenitic material, FOX A7 Cr-Ni-Mn electrode (5 mm) with a low carbon content was proposed for the intermediate layer.

The image of the selected weld deposit macrostructure (Fig. 1) presents the mode of applying the deposit layers and the extent of heat affected zone. The intermediate Cr-Ni-Mn layer was deposited at approx. 2 mm thickness (150 A) using a filled electrode (welding parameters: 264-312 A; 28.7-29 V; 10 m/min) with pre-heating to 350 °C. The weld deposit was milled off to the prescribed slot depth, the operational wear was simulated by grinding weld metal. This was followed by welding on the "repair" layers with pre-heating to 110 °C (welding parameters: 236-244 A; 28 V; 9.5 m/min). The chemical composition of the material combination applied is shown in Table 1. The overall mixing of the deposit layer is reflected in the areal chemical microanalysis.

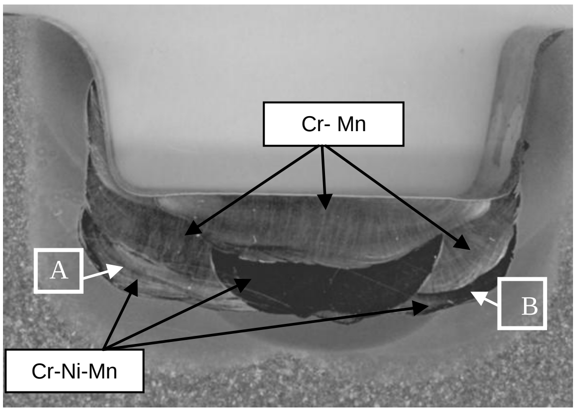

Fig. 1. Macrostructure of experimental weld deposits

Pre-heating is normally not recommended in the application of filler materials of this composition. In our application, the proposed pre-heating temperature is based on the nature of the base material. Given the material combination used, issues concerning the diluted filler metal and the possible melting loss of the alloying elements are among the crucial criteria when designing the geometry of overlay welded grooves and technological welding parameters.

The examination of the structural stability of the weld deposits was based on a theoretical analysis using available parametric dependencies on the chemical composition and possibilities

Table 1

Chemical composition (in wt. %) of used materials

	C	Cr	Ni	Mn	Si	Mo
FOX A7 (Cr-Ni-Mn)	0.093	18.79	8.67	6.53	0.81	0.02
SK AP-O (Cr-Mn)	0.35	12.80	0.02	15.80	0.30	0.02
base material (BM)	0.58	-	-	1.11	0.26	-
FOX A7- chemical microanalysis (500x500μm)	-	12.95	5.12	5.56	0.61	-

of phase changes during the cooling and solidification. The focal point of the presented works is a comparison of the quoted assessment processes with experimentally induced limit conditions, i.e., an analysis of the specific conditions leading to damage.

4. Results

As concerns the limits for heat input for repair overlaying welding, it was discovered that the combination of materials and technological parameters tested does not bring a risk of formation of unstable structures resulting in cold cracks in carbon steel. On the contrary, induced decarbonisation of the rail steel up to approx. 0.15 mm deep was registered by means of increased proportion of structurally free ferrite. The formation of cracks in the intermediate layer (the Cr-Ni-Mn material) was identified as the limiting effect. Only one weld deposit layer, produced as part of the initial overlaying of the milled rail groove, showed damage (Fig. 1 -area “A”, Fig. 2). The remaining layers of this type of material, comprising both the fusion zone with the base material and the repair layer, showed a mostly homogeneous austenitic structure free of defects. Since the initial deposit layers (areas A, B in Fig. 1) were produced with the same technological parameters and welding area geometries, this result reflects the effect of instability of the manual overlaying welding process.

Large structural heterogeneities were identified in the final intermediate layer structure. Clearly in reaction to local transition in composition between the welded materials, zones of a martensitic structure were formed, oriented parallel with the fusion zone, i.e., along the front of the progressing crystallisation line of the deposit layer. However, cracks only formed along the interface of the columnar grains of the intermediate layer, meaning they may have been caused in part by liquation or diffusion processes towards the grain boundary. The analyses focused chiefly on the effect of interdendritic segregation of the alloying elements. Martensitic transformation was observed with a clear preference for areas with primary dendritic branches (Fig. 3); martensite also formed locally along grain boundaries. The crack initiation was oriented exclusively to grain boundaries flanked in this way.

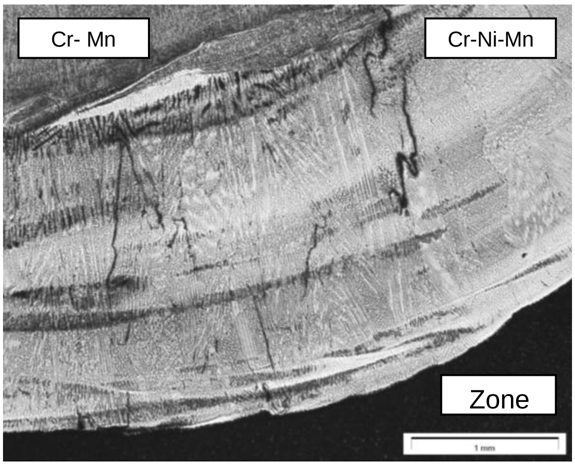

Fig. 2. Damaged part of the weld deposits

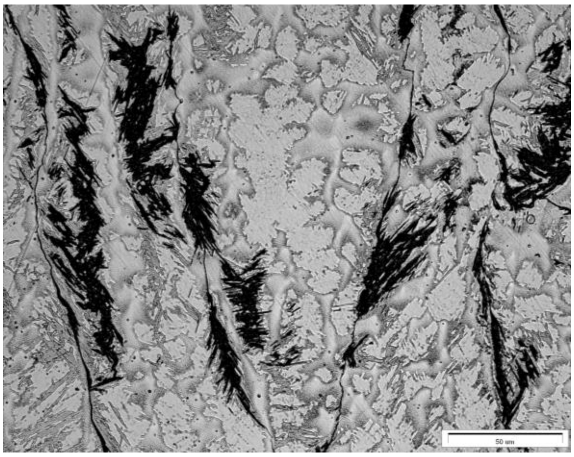

Fig. 3. Heterogeneous structure of the interlayer

The results of the chemical microanalyses of the structurally contrasting areas of the weld deposit layer are shown in Fig. 4 in contrast zone vs. dendritic heterogeneity.

When estimating the potential risk of formation of undesirable structural components in the different fusion line (BM / Cr-Ni-Mn, Cr-Ni-Mn / Mn-Cr, BM / Mn-Cr), we can use the Schaeffler diagram as the starting point (Fig. 5). Both the weld deposit

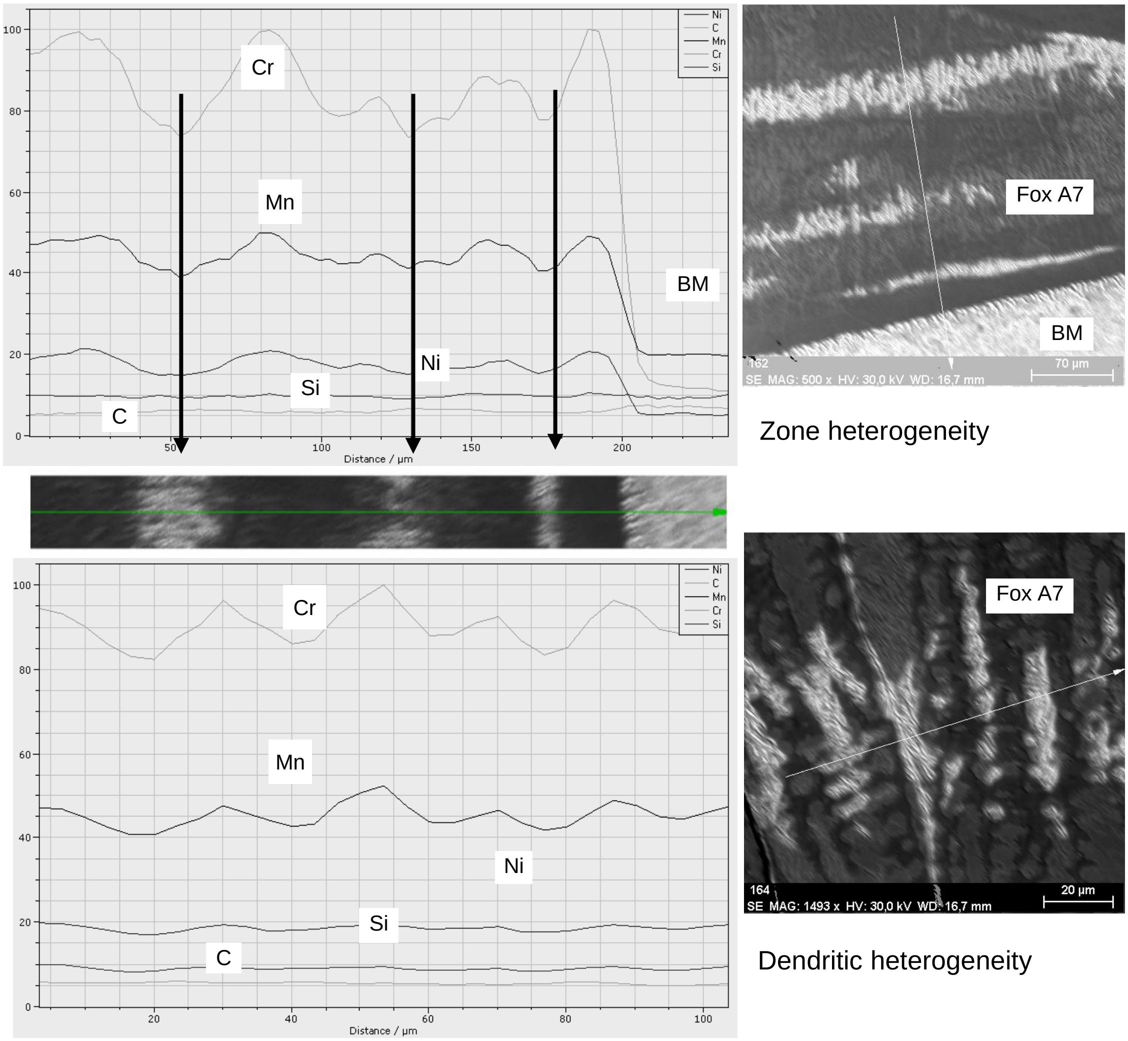

Fig. 4. Zonal vs. dendritic chemical and structural heterogeneity

materials used fall into the purely austenitic area of the diagram, without any delta-ferrite in their structure. The position of the point representing Cr-Mn steel indicates increased risk of hot cracks in weld deposits.

Highlighted points 1 – 3 represent the actually induced chemical heterogeneity, reflecting both zonal and interdendritic segregation of the alloying elements. With respect to the chemical analysis method employed, the carbon content cannot be inferred from local measurement at a sufficient accuracy. For the needs of this study, the local differences in carbon content were determined by the proportion established in linear analyses conducted transversely into unaffected base material. Interval reflects dissipation of the line chemical analysis. Over 58 % dilution leaded to martensite transformation; this assessment included the formulation of the limit Ni/C ratio leading to the initiation of cracks - about Ni/C = 8, in comparison to Ni/C = 13 in the interdendritic areas of the diluted area. An adequate reinforcement was evaluated by measuring of the hardness gradient; hardness of the critical areas reached over 490HVm (Fig. 6).

5. Discussion

Difficult points in respect of the technique in question may include redistribution of carbon from the grain interior to grain boundaries, and

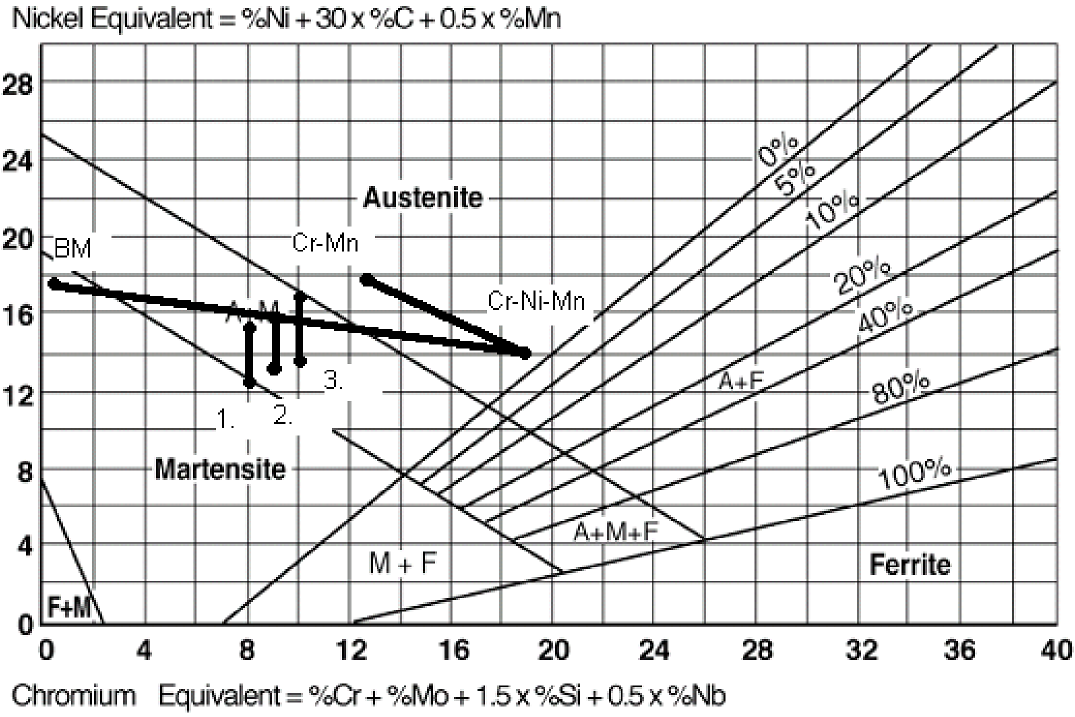

Fig. 5. Schaeffler diagram, showing the situation of joining steels (1-martenzite out of grain boundary, 2-martenzite on grain boundary, 3-austenite)

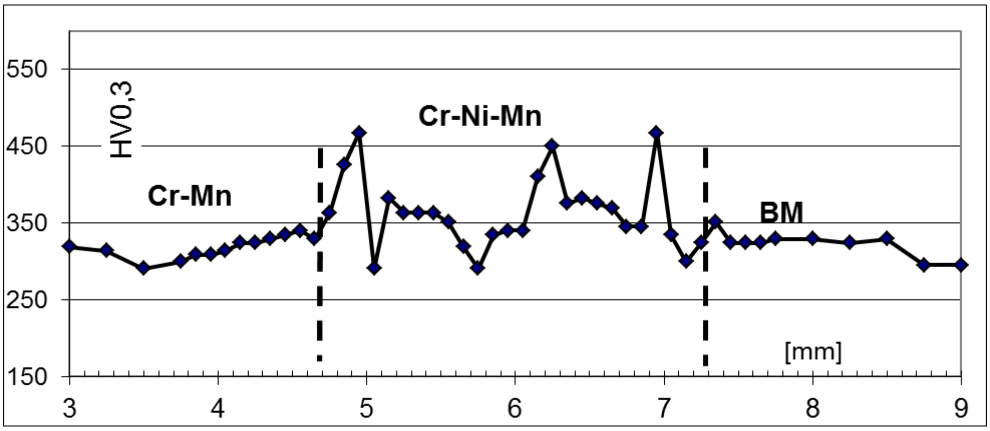

Fig. 6. Hardening in intermediate layer

redistribution of carbon at the fusion line [12, 13]. In the application in question, given the dynamic nature of the operating loads, this process chiefly brings a risk of reducing toughness [14]. The analysis results indicate that the proposed technique is not a heat input that would lead to precipitation of carbides along grain boundaries. The ductility decreased and the intercrystalline cracks were initiated as a result of localised martensitic transformation.

The redistribution processes directly along the fusion line were limited to local decarbonisation of the pearlitic steel. Undesirable effects connected, e.g., with uphill carbon redistribution, confirmed in this combination, bring a risk in thermal additions greater than that in the repair welding tested.

Microstructure evolution and, as a result, the possible formation of defects, are strongly affected by the shape of the grains along the fusion boundary. Due to different composition of the welded steels, normal epitaxial growth may be suppressed. This can result in the formation of zone, what are called type II boundaries, which run roughly parallel to the fusion boundary. Analysed welding joint is therefore typical for cracks along the fusion zone, usually referred to as disbonding [15, 16]. Local depletion of the alloying elements overcame this tendency under examined experimental conditions. Significant dendritic heterogeneity allowed the preferential martensite formation in the direction of crystallization, followed by the similar oriented carbon redistribution.

6. Conclusions

The structural stability of the material combination tested is affected by several simultaneous processes; experimental study requires the distinction of fundamentally different concurrent mechanisms.

The issue of supercritical mixing of the intermediate layer with the base material was identified as a limiting effect for the technique in question. Due to their composition, both the welded metals bring a risk of hot crack formation even without the mixing effect. In the application in question, the final tendency of the intermediate layer material to a certain damage mechanism depends on the crystallisation process, controlled by local differences in the content of alloying elements. The dendritic segregation resulted in a substantial enrichment with chromium along the axes of the primary delta-ferrite crystals; austenite crystals formed in the remaining melt (enriched with nickel). The transformation of ferrite to austenite was not complete. Depending on the degree of the local decrease in the alloying elements (and the final proportion of the austenite vs. ferrite-forming elements), two final effects may occur:

- a ferritic skeleton with all the known positive effects on joint quality (including suppression of the tendency to form hot cracks) will remain along the dendrite axes;
- martensite will form, which leads to initiation of intercrystalline damage in combination with decreasing cohesive strength of grain boundaries.

The occurrence of these defects substantially affects the tension (particularly the mutual orientation of grains and tensile components of stress) and the conditions for adding liquid metal in the solidifying area. In reality, therefore, the conditions for the formation of cracks are considerably affected by the geometry of the welded area and the entire structural node, and can only be generalised to a very limited degree outside the specific experimental conditions.

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