HORIZONTAL SPLIT-WEB FRACTURES OF FLASH BUTT WELDED RAILS

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ABSTRACT

Generally about 80 percent of railway tracks are welded by flash-butt welding that consists of electrical heating and hydraulic forging. The service performance of such welds is affected by their ability to support the service loads without fatigue damage or fracture. Horizontal split-web fractures, which may involve splitting of rail head, are of main concern because of potential risk of a catastrophic derailment. In this paper, failure analysis of three broken flash welded rails is presented. The investigation included chemical analysis, hardness measurement, SEM fractography, and microstructural characterization. The crack path consisted of two regions where after initial propagation parallel to the rail surface it tended to propagate on a slant surface. Fractographic analysis showed that high cycle fatigue was the main failure mechanism. Crack initiation sites were located at welded zones and were associated with large inclusions that were not properly removed during chiseling of upset material. Fatigue crack propagation was confined to planes parallel to the rail surface. Crack branching occurred after considerable unstable fast fracture. Finally it is clarified that trapped inclusions, residual stresses, track irregularities and dipping from localized wear in soft regions of weld, associated with variations in pearlitic microstructure, contribute to horizontal split-web fractures.

Keywords: Combustion chamber, Insert bolts, Intergranular creep rupture, Nimonic 80A.

1. INTRODUCTION

The utilization of the welding method for joining rails has since then been applied increasingly, and it is now standard practice all over the world [1,2]. The most important reasons to use continuous welded rails, in contrast to bolted rails, are the lower maintenance cost and the improved dynamic behavior of the train–track–rail system. Nowadays whenever possible, rails are joined by welding. There are primarily two welding processes used today, flash-butt welding and alumino-thermic (thermite) welding, but other methods are also employed such as gas pressure welding and enclosed arc welding. About 80–90% of weld tracks are flash-butt welds. The thermite welding method is a casting method and it is the most common method used to repair of broken rails and welds. In thermite welding, the rails are laid with a gap and a ceramic mould is placed around the rail. The alumino-thermic mixture is ignited and molten steel flows down the gap to make up the weld. Defects in thermite welds are often lack-of-fusion, shrinkage cavities, hot tears, gas pockets and inclusions from entrapped slag or mould [3-5].

Flash-butt welding is a type of the resistant welding processes. The process consists of two primary stages: Flashing and Upsetting (Figure 1). In this process, the ends of the pieces to be welded are connected to the secondary circuit of a transformer. While one piece is held firmly by a clamping device attached to a stationary platen, the other piece is clamped to a movable platen. The ends to be welded are allowed to touch allowing heavy currents to pass through the peaks or asperities of the edges and providing resistive heat to the edges. These bridges start melting and at greater velocities, the molten bridges are broken and thrown off as flash particles from the joint. This cycle of the formation and collapse of bridges goes on as the movable platen advances and is nominated flashing. When the conductive heat has sufficiently heated the metal behind the faying surfaces on either side to ensure adequate plasticity, the flashing current is stopped and the ends are butted against each other with great force that is called upsetting. This ensures that the molten metal, oxides and other impurities are extruded out of the surfaces to be joined and clean metal are exposed and hence, satisfactory bonding takes place during final stage of welding. The expelled materials during upsetting form a ragged flash or fin around the joint (Figure 1). Immediately after the weld has been completed, a hydraulic shearing device integrated in the welding head removes the welding upset [6].

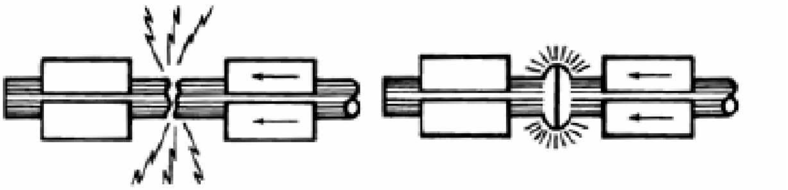


Figure 1. Flashing and upsetting stages of flash-butt welding process[6].

Contrary to thermite welds, flash-butt welding process, with it's limited defects and changes to the metallurgical character of the rail, reduces the possibility of loss of running surface smoothness due to the providing hardness levels which are comparable with the parent rail; Hence it can reduce weld batter (localized plastic deformation) and localized wear which results in increased impact loading and may contribute to premature failure of the welds, thus producing a very high quality continuous welded rail [4].

In despite of high integrity of the flash welded rails, horizontal split web (HSW) fractures of weld zone (Figure 2) are frequently observed. Costs of rail failures include remedial treatments, inspection, pre-emptive treatments and train delay. Besides, HSW fractures may lead to catastrophic derailment of vehicles due to the splitting of a portion of running surface of rail head, the consequences of which can include death, injury and loss of public confidence. HSW fractures are likely to be a concern as business demands for higher speed, higher axle loads, higher traffic density and higher tractive forces increase.

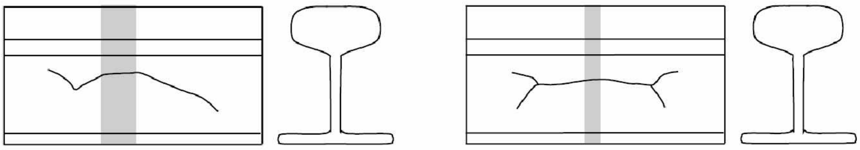


Figure 2. Horizontal split-web (HSW) fractures of weld zone [7].

Figure 2 shows fracture path of such fractures, schematically, illustrating that crack propagates almost parallel to the rail surface in the rail web and then branches toward rail head and base at the angle of about of 45°. HSW fractures occur in both fatigue and overload types. Mutton et al. [5] indicated some features and factors contributing to overload type of HSW fractures such as radius of curves, vehicle hunting and large inclusions in thermite welded rails. The present study was therefore carried out so as to figure out the failure causes of fatigue type of horizontal split web fracture of flash welded rails considering both the metallurgical and mechanical aspects.

2. EXPERIMENTAL METHODS

Three HSW fractured flash welded rails were investigated. The chemical composition of the base metal was determined by using a standard spectrometer analyzer. The broken flash welded rails were first subjected to visual examination, macro-fractography and photo documentation and were analyzed in an as-received condition. Then, required samples for chemical analysis, microstructural analysis and micro-fractography were cut from appropriate locations. Chemical analysis of the failed rails was conducted using optical emission spectroscopy. The specimens for microstructural study were prepared as per standard metallographic techniques and etched with 2% natal and were studied by optical microscope. The fracture surfaces were cleaned ultrasonically by 6 N hydrochloric acid solution containing 2 g/L of hexamethylene tetramine as the inhibitor and were studied using a scanning electron microscope equipped with an energy dispersive analysis facility.

3. RESULTS AND DISCUSSION

Chemical composition of the base metal is given in Table 1. The composition of rail steel clearly falls within standard chemical specification of the grad 900A rail steel. Tensile strength of this rail steel grad is approximately 900 MPa [6]. As can be seen in table 1, the carbon content is slightly lower than eutectoid steel and therefore, the microstructure of the rail essentially consists of pearlite with the small volume fraction of ferrite that covers of the grain boundaries of pearlite. Pearlitic rail steel has been predominantly used for their excellent wear resistance because of their lamellar hard phase (cementite), plastically deformed due to the Contact stresses between the wheel and rail and consequently were aligned parallel to the wear face (running surface of the rail) and a mosaic microstructure of the hard cementite flakes is produced that has superior wear resistance when compared with bainitic or martensitic microstructures which cannot adapt and enhance their microstructures in this way.

Table 1. Chemical analysis of the fractured rails

Source of data	Composition (wt. %)					
	C	Si	Mn	P	S	Fe
Sample 1	0.76	0.29	1.05	0.009	0.014	Balance
Sample 2	0.74	0.27	0.94	0.011	0.016	Balance
Sample 3	0.75	0.25	0.91	0.018	0.035	Balance
900A	0.6-0.8	0.5-0.1	0.8-1.3	0.04 max	0.04 max	Balance

The three fractured flash welded rail which exhibit similar fracture features are shown in Figure 3. The nearly horizontal fracture plane passing through the flash weld fracture and macroscopic direction of crack propagation which is determined with the help of chevron marks on the fracture surface are shown in Figure 4. The crack propagates parallel to the rail surface (horizontally) in the vicinity of the rail web and then branches toward rail head and base at the angle of about of 45°.

Figure 3. Fractured flash welded rail

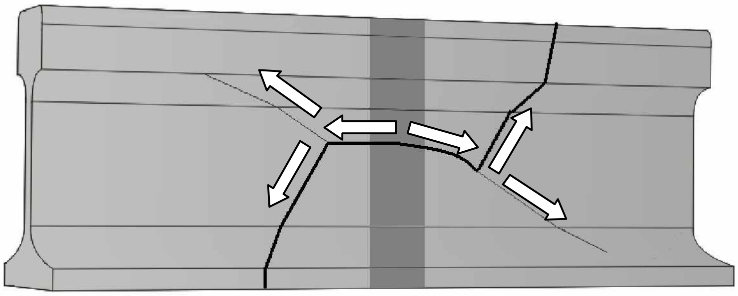
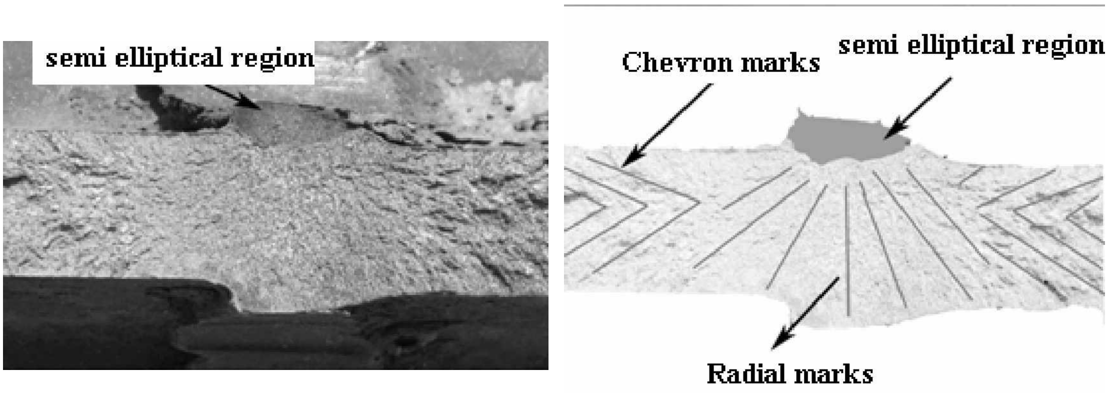


Figure 4. Macroscopic crack propagation direction.

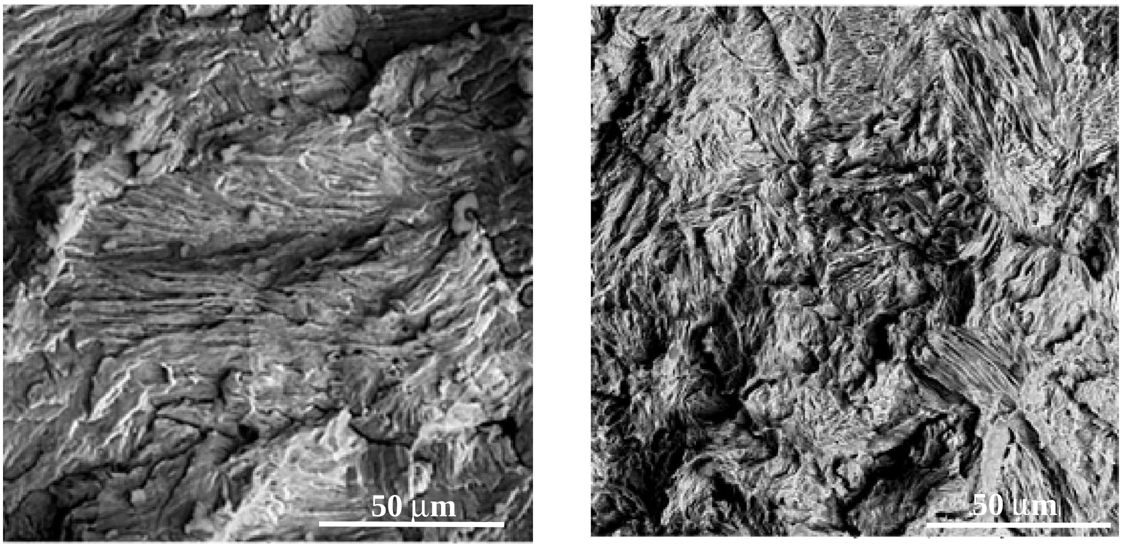
As shown in Figure 5 (a,b) a small semi elliptical region can be seen in the fracture surface of the horizontally crack with a clearly defined demarcation. This region which exhibits a smooth appearance has been exactly located near the expelled materials during upsetting (upset materials). Radial and chevron marks are observed in the relatively rougher region outside of the semi elliptical region. The two macroscopically distinct regions of the fracture surface are more clearly shown in a schematic drawing in Figure 5(b).



(a) (b)

Figure 5. (a) Macroscopic fracture surface appearance and (b) schematic of distinct regions and fracture surface markings of a horizontal split-web fracture.

Fracture surface of semi elliptical region consisted of complex surface topography. Examination of fracture surfaces by SEM at higher magnifications (Figure 6) reveals adjacent regions with differently oriented parallel markings which are indicative of extensive microstructural influence on the microscopic crack growth direction during slow and stable crack growth. Microstructural examinations indicate that this type of fracture morphology is closely related to the layered structure of pearlit, which consists of ferrite and cementite.



(a) (b)

Figure 6. Complex surface morphology of the semi elliptical region.

The fracture surface exhibits a clear change in fracture mechanism outside the semi elliptical region. The dominant fracture morphology changes to that of fan-shaped cleavage facets characteristic of a low energy brittle fracture process (Figure 7). Consequently, the boundary of the semi elliptical region clearly demarcates the position of the crack front at the onset of transition from slow stable cyclic crack growth to fast unstable final fracture.

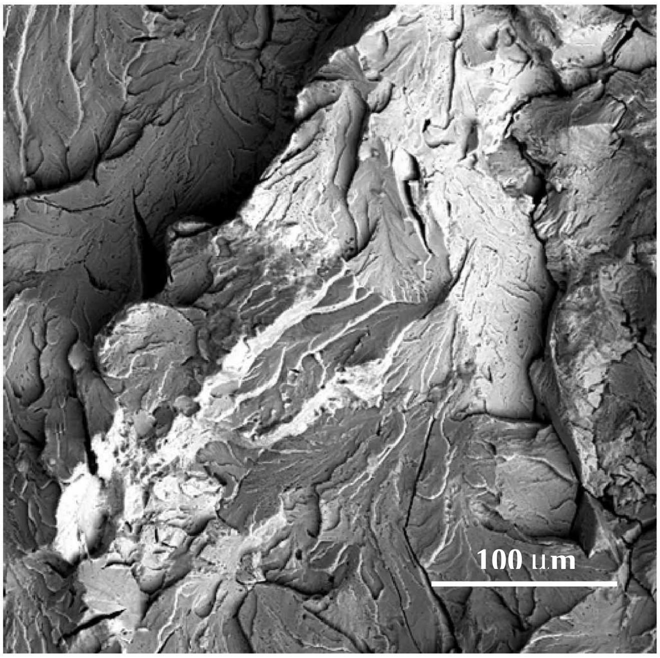


Figure 7. Fan-shaped cleavage facets outside the semi elliptical region.

Based on the above macroscopic and microscopic observations cyclic crack growth due to fatigue can be identified as the main contributing factor to the failure of flash welded rails. The small size of the semi elliptical crack at the onset of unstable fracture is indicative of the low fracture toughness of the rail steel, which is reported to be about 30 MPa.m$^{1/2}$ [8], and the high stress levels.

A low magnification SEM fractograph of the Semi elliptical fatigue region is shown in Figure 8. Beach marks and ratchet lines are observed on the fatigue fracture surface which trace back to the crack initiation site associated with the upset material on the weld joint at the rail surface. EDS analysis of the fracture surface at the initiation site shown in Figure 9 reveals the presence of oxides in this region.

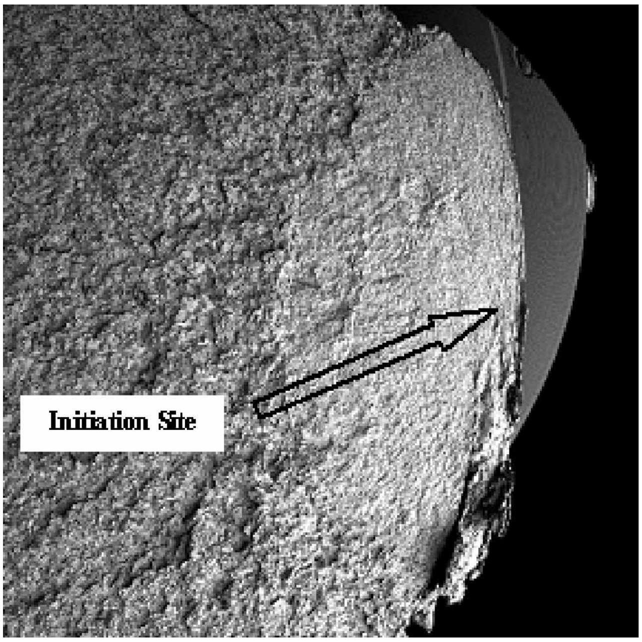
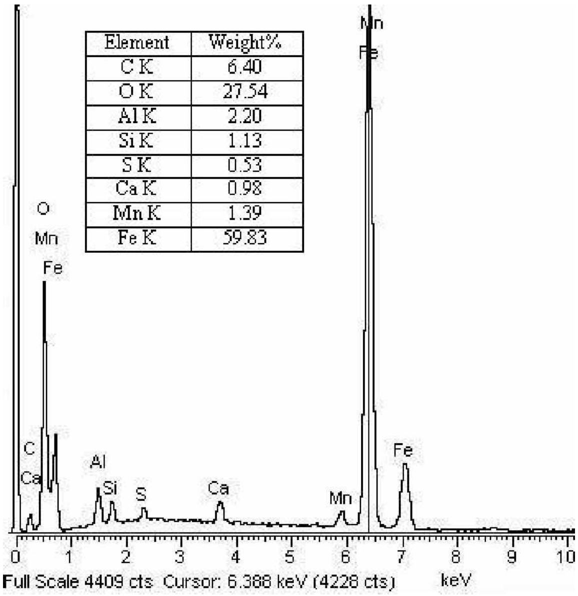


Figure 8. Low magnification SEM fractograph of the Semi elliptical fatigue region.



Element	Weight%
C K	6.40
O K	27.54
Al K	2.20
Si K	1.13
S K	0.53
Ca K	0.98
Mn K	1.39
Fe K	59.83

Figure 9. EDS analysis of the fracture surface at the initiation site.

Presence of oxide impurities is confirmed by microstructural study of metallographic sections directly beneath the fracture surface. Large oxide inclusions, which were trapped during removal of upset material by the hydraulic shearing device at the end of the welding process, can be clearly seen in Figure 10. In addition, cast structures and decarburized materials can be seen at the weld surface. Porous and particulate materials that have not been compacted during the upsetting are also observed. Microstructural study of the section perpendicular to the fatigue crack reveals the weld surface is highly porous and contains entrapped oxides penetrating up to a depth of 3 mm beneath the surface. These defects produce a very inferior quality weld surface which facilitates and accelerates nucleation of fatigue cracks.

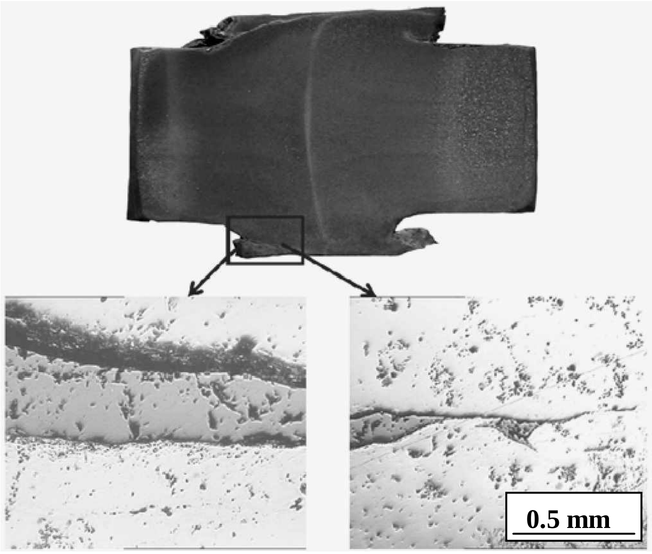


Figure 10. Large oxide inclusions trapped during removal of upset material.

Cyclic tensile stresses perpendicular to fatigue crack surface are prerequisite for observed fatigue crack propagation. Indeed stress components of tensile character must develop near the web region of the rail in the vertical direction. It can be seen from Figure 11 that the tensile stress component can develop due to eccentric vertical load of the wheel passing over the rail.

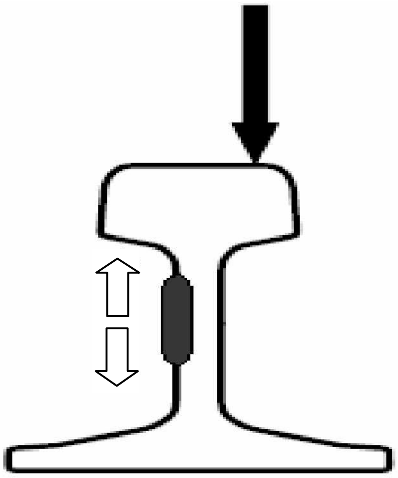


Figure 11. Development of tensile stresses in the web due to Eccentric vertical load of the wheel.

High tensile residual stress can be developed as a result of the thermal cycle of flash butt welding process. In the rail web of the weld region, both vertical and longitudinal components of the residual stress field are strongly tensile. Vertical tensile residual stress in the web's middle of the weld region has been reported by some researcher. Skyttebol et al. [3] showed through modeling and experimental measurements that vertical tensile residual stress in the web's middle of the weld region is about 500 MPa (Figure 12). Smaller compressive or tensile stresses that can be produced during wheel passing over the rail are superimposed on residual tensile stresses and therefore inferior tensile-tensile cyclic stresses are developed. More inferior cyclic stresses are produced when torsional loading is increased; for example when the vertical load is applied near the field side of the rail and/or the lateral wheel loading is increased due to the curves or vehicle hunting. These cyclic stresses are not developed in the rail because the residual stress in the rail is quite different from the weld region and hence these types of fractures are not observed in the non-weld regions.

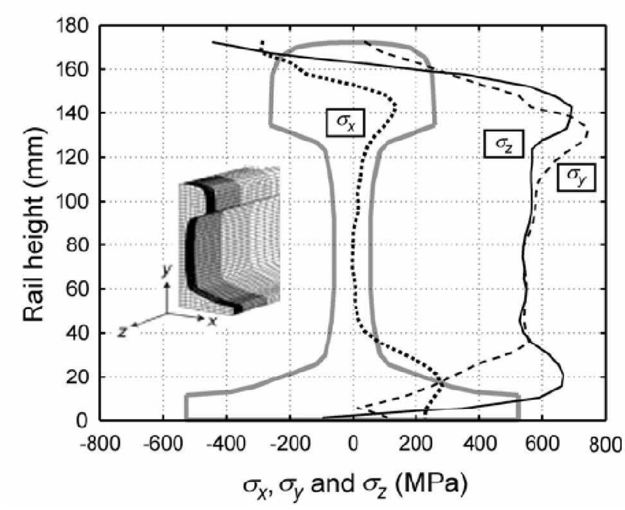


Figure 12. Vertical tensile residual stress the weld region (σ_y) [3]

Dynamic effects resulting from curves and vehicle hunting, track-top irregularities or misalignment of two adjacent welded rails can significantly increase the rail stresses and consequently increase the tendency for this type of fracture. Dynamic forces can significantly reduce the critical size of fatigue cracks. If they occur sufficiently frequently, they can increase fatigue crack growth rates.

4. CONCLUSIONS

1- Based on fractographic studies fatigue fracture was identified as the main contributing failure mechanism in the horizontal split-web fractures of flash welded rails.

2- Fatigue cracks initiated at large oxide inclusions which were trapped during removal of upset material at the end of the welding process.

3- The semi elliptical fatigue fracture surface exhibited differently oriented parallel markings neighboring regions whereas the dominant fracture morphology in the final fracture region that of fan-shaped cleavage facets.

4- The small size of the semi elliptical crack at the onset of unstable fracture can be attributed to the low fracture toughness of the rail steel, and the high stress levels.

5- The cyclic stresses required for fatigue crack initiation and propagation can be developed as a result of superposition of the eccentric vertical load of the wheel passing over the rail and weld residual stress patterns.

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