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D4.6.1 –The influence of the working procedures on the formation and shape of the HAZ of flash butt and aluminothermic welds in rails

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Glossary

Abbreviation/acronym	Description
HAZ	Heat affected zone (can also be called heat softened zone)
HC	High carbon
HPW	High performance weld
FB	Flash butt
SkV	Aluminothermic weld with optimized HAZ (German denotation: “Schnellschweißverfahren mit kurzer Vorwärmung”)

1. Executive Summary

One of the degradation mechanisms of welds is the differential wear between the bulk metal and the heat affected zone (HAZ) arising from the difference in hardness and wear resistance in the two regions. Consequently, welds exhibiting softened critical heat affected zones (HAZ's) wear away preferentially during service in track, leading to the development of localized wear dips or 'weld batter' on the running surface of the welded rail.

In the case of Flash Butt Welds, this degradation mechanism has been countered by reducing the width of the HAZ, particularly, the thickness of the band of lower hardness so that the weld is no longer visible to the wheel. The development of the Narrow HAZ welding procedure, patented by Corus, and the resulting properties are described in this document.

The process parameters of flash butt welding that contribute towards the formation of the heat affected zone have been critically examined and optimised with the aim of significantly reducing the HAZ width towards the narrower end of that specified in EN 14587-1. The process has been applied to all the commonly used rail steel grades and a number of rail sections. The success of the new process has been demonstrated through the results obtained for Grade 350 HT, 60E1 rail. Data for bend strength, hardness profile, and bending fatigue strength all demonstrate full compliance with EN 14587-1.

In the aluminothermic welding process the HAZ is produced by the heat input during preheating and by the superheated molten steel. By modification of the preheating parameters and the pouring system the width of the HAZ can be influenced. An additional possibility to influence the HAZ is a post heat treatment of the weld after the final grinding process.

The influencing process parameters to alter the width of the HAZ have been discussed. SkV-Elite is the welding process that provides the narrowest HAZ compared to the other welding processes from Elektro-Thermit. Nevertheless, the width of the weld and the width of the HAZ need to be considered with regard to the properties of the complete welding joint. The change of properties along the complete weld has to be controlled to optimize the performance.

Within this project HPW has been chosen as welding process because of its innovative welding procedure, that a selective alloying technique allows decoupling the properties of head and base of the weld. The high wear resistance of a hard head can be combined with the higher ductility of a base with lower hardness.

2. Introduction

One of the degradation mechanisms of welds is the differential wear between the bulk metal and the heat affected zone (HAZ) arising from the difference in hardness and wear resistance in the two regions. Consequently, welds exhibiting softened critical heat affected zones (HAZ's) wear away preferentially during service in track, leading to the development of localized wear dips or ‘weld batter’ on the running surface of the welded rail. This, in turn leads to the generation of high impact loads, which increase in magnitude with both increasing depth of weld dipping and increasing train speed. The high impact loads generated by "dipped" welds have been observed to lead to additional track related problems such as increased wear of wheel sets and bogies, development of corrugations and squats as well as increased noise level.

In the case of Flash Butt Welds, this degradation mechanism has been countered by reducing the width of the HAZ, particularly, the width of the band of lower hardness (“soft” sub-critical HAZ zones) so that the weld is no longer visible to the wheel. The development of the Narrow HAZ welding procedure, patented by Corus, and the resulting properties are described in this document.

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3. Flash Butt Welding

A Schlatter GAAS 80 rail welding machine was employed for the narrow HAZ FB weld development; however it should be stated that the general principles of the development are equally applicable to other rail welding machines.

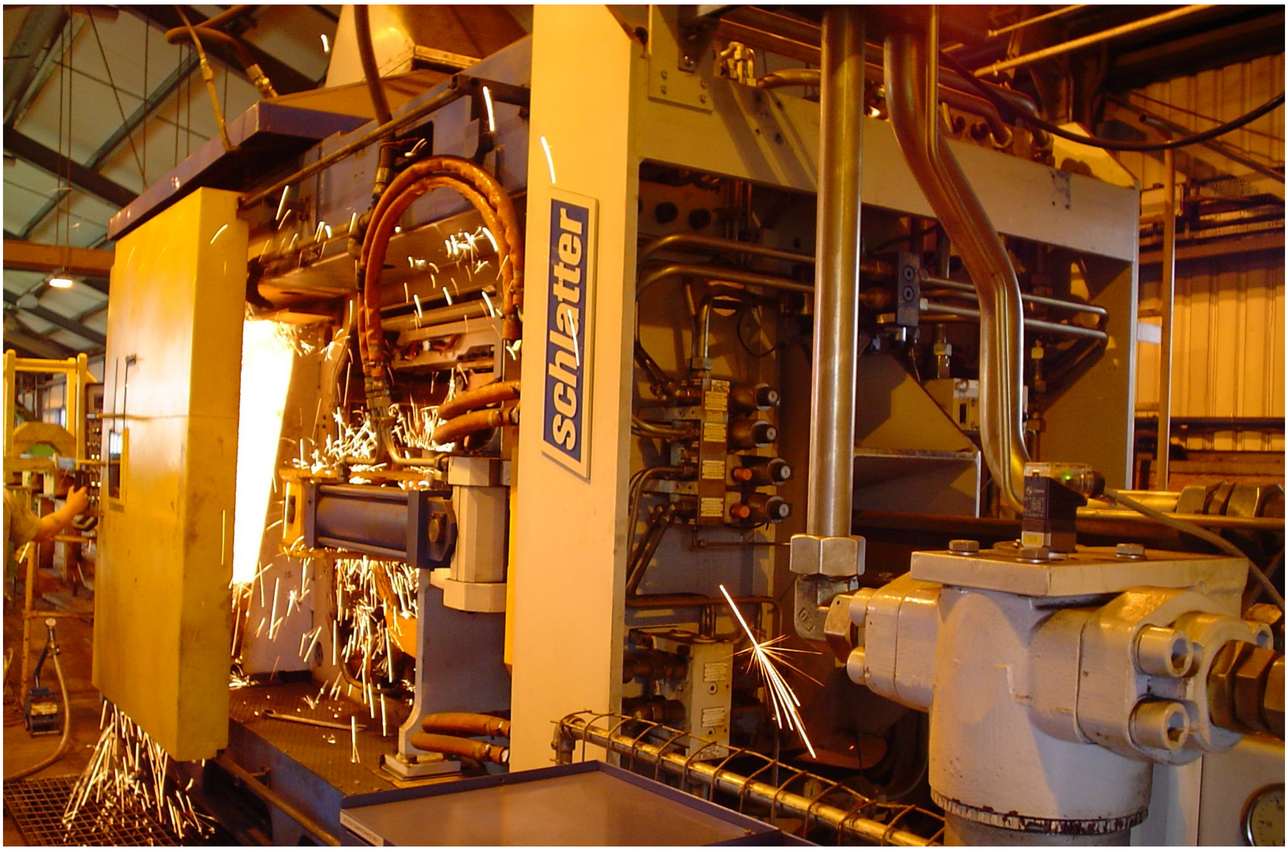


Figure 1 - Schlatter GAAS 80 Flash Butt Welding Machine

3.1 Development of Narrow HAZ Flash Butt Welds

A twofold approach was adopted to achieve the desired aim of producing a factory flash butt weld with an HAZ width significantly narrower than those of standard production welds.

- As low a heat input as possible to achieve adequate weld consolidation
- As low a conduction of heat away from the weld interface into the body of the rail as possible

The achievement of the above objectives required close examination of the standard welding parameters and lead to the following key changes to arrive at a Narrow HAZ weld:

- A slightly longer initial flash duration giving a longer localised heating cycle
- A considerably lower number of preheats aimed at reducing the total heat input

- Significant reduction in the durations of the preheat "On" and "Off" periods aimed at reducing both the overall heat input and the total time for the heat to be conducted away from the weld interface.
- A shorter final flash duration giving a shorter localised heating cycle and reducing both the heat input and the heat conduction time
- Lower forging (upset) distances – this is a direct consequence of the significantly reduced heat input levels

A final requirement in this development programme was to test the applicability of the procedure to the various rail grades.

3.2 Results

Although procedures have been developed and assessed for Grades 220, 260, 350HT and Corus Rail 400 MHH, example results for Grade 350HT have been presented below to demonstrate the success of the development. The following aspects have been considered:

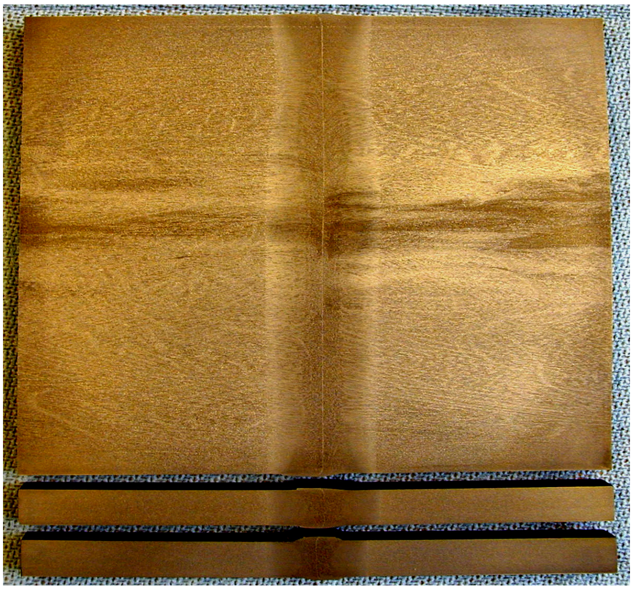
1. Effect of the number of pre-heats on bend test results and HAZ profiles
2. Hardness profile
3. Bending Fatigue Strength

3.2.1 Effect of Number of Pre-heats

Although all the factors itemised in Section 3.1 make useful contributions towards the production of a sound narrow HAZ, it is the contribution of the number of pre-heats that is considered most significant. The bend test results on the trial undertaken with Grade 350HT, 60E1 Rail section are shown in the Table 1 while the details of the HAZ widths are shown in Table 2.

Weld Number	Weld Type	Number of Preheats	Weld Upset (mm)	Bend Test Load (kN)	Bend Test Deflection (mm)	Bend Test Sample Broke / Not Broke
1	Standard	11	13.5	1675	34	Not Broke
2	Standard	11	13.4	Metallurgical Sample		
3	Narrow	4	10.3	2010	60	Not Broke
4	Narrow	3	10.3	1815	42	Not Broke
5	Narrow	3	10.8	1831	36	Not Broke
6	Narrow	3	10.7	1825	36	Not Broke
7	Narrow	3	10.5	1830	35	Not Broke
8	Narrow	3	10.8	1829	36	Not Broke
9	Narrow	3	10.9	Metallurgical Sample		

Table 1 - Bend Tests Results for Grade 350HT, 60E1 Rail



Standard Weld

Narrow HAZ Weld

Position	HAZ Width (mm)	
	Standard Weld	**Narrow HAZ Weld**
Rail Running Surface	37	26
20 mm Below Rail Running Surface	35	21
86 mm Below Rail Running Surface	37	23
20 mm Above Rail Foot Base	38	20
Rail Foot Base	38	23
Rail Foot Tips (A and B)	32, 36	24, 24

Table 2 - HAZ Profiles

3.2.2 Hardness Profile

The hardness profiles from the 350HT, 60E1 rails for the standard (post weld enhanced cooled using compressed air) and Narrow HAZ (normal air cooled) welds are shown in Figure 2 below.

3.2.3 Bending Fatigue Strength

Strength in bending fatigue is an important requirement in the welding specification of all railways and consequently, it was necessary to demonstrate that the changes in welding parameters deployed to achieve narrow HAZ width had not compromised this important attribute. The data shown in Figure 3 below clearly demonstrates that the fatigue performance of Narrow HAZ welds is very similar to that of the standard welds.

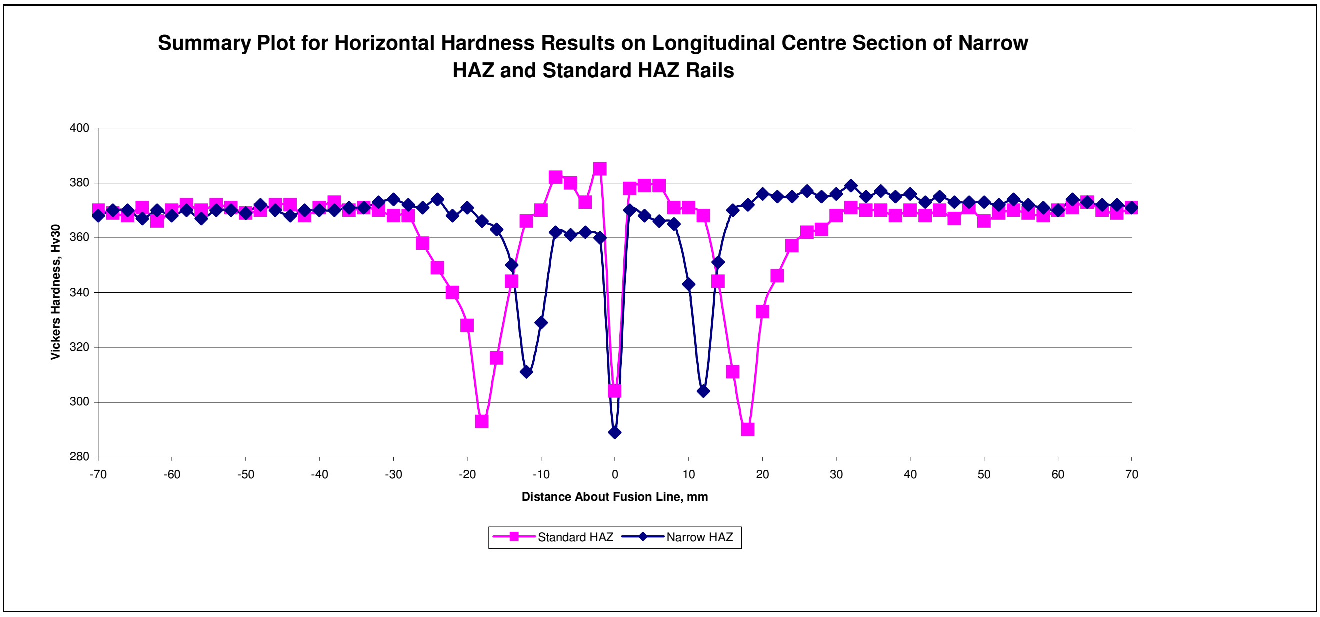


Figure 2 - Hardness Profiles of Standard and Narrow HAZ Welds

Figure 3 - Strength in Bending Fatigue of Welds

4. Aluminothermic Welding

4.1 General Considerations

Aluminothermic welding is – beside Flash Butt Welding – the most important welding process to produce the continuously welded track. Comparable to FB welding, during the aluminothermic welding process a heat affected zone will be generated in the parent rails.

For aluminothermic welding not only one clearly defined welding procedure is available but a couple of different welding procedures exist side by side to take different rail types (Vignoles rails and grooved rails), different rail profiles or different grades of the rails into account. For all of those aluminothermic welding processes a high number of influencing factors exist that are having a contribution to the shape and width of the heat affected zone.

The most important parameters are listed in the following. All relevant process parameters which can be influenced by the welder such as the preheating process and gap width are specified in the code of praxis for the individual welding procedures.

- Profile and type of rails
- Gap width between the rails prior to welding process
- Temperature of the rails
- Weather conditions
- Preheating
  - preheating time
  - gas pressures (e.g. propane and oxygen)
  - burner type
  - burner height
  - quality of the used gas (calorific value)
- Pouring system / mould geometry
- Temperature of superheated liquid steel at the beginning of the welding process
- Mass of liquid steel that is used to fill the gap between the rails

Most important is the pouring system that specifies exactly the geometry of the moulds. For each of the existing welding processes the mould geometry needs to be adjusted with respect to the different rail profiles. Based on these considerations the process parameters are fixed in the codes of praxis.

However, aluminothermic welding is a special kind of casting process and the width of the HAZ will be a result of the heat of the metal and the heat flux during solidification and further cooling of the weld.

An additional possibility to influence shape and width of the HAZ is a post heat treatment after grinding.

It is impossible to make an existing HAZ smaller than before by any kind of thermal treatment – it only exists the possibility to choose a heat treatment process that covers the effect of the original welding process. The superimposition of the second heat treatment might finally lead to properties of the weld that are better than in the initial condition.

Up to now no systematic investigation is available that clearly shows the influence of the process parameters on the width of the HAZ. It is obvious that for aluminothermic welding the presence of the HAZ can never be avoided. Although different welding procedures exist (and despite the high number of possible influencing factors) it is believed that the width of the HAZ cannot drastically be minimized. The heat of the liquid metal and the temperature of the rails will enforce that the width of the HAZ cannot fall below a minimum value. This minimum has not been determined yet but the complete aluminothermic welding process does not allow varying the process parameters to a large extent. Therefore, the width of the HAZ will always be in the same order of magnitude.

In Figure 4 longitudinal sections of welds are given that are generated by the use of different welding procedures (HPW, SkV-Elite and SoW-5). Based on the experience up to now the welding process SkV-Elite results in the smallest HAZ compared with e.g. HPW or SoW-5.

This knowledge may not lead to a separation of welding processes with a comparatively large HAZ and a comparatively narrow HAZ. This kind of separation would not be helpful because the properties of the weld are not only determined by the width of the HAZ. The properties of the weld need to be regarded along the complete weld (parent rail – HAZ – weld metal – HAZ – parent rail).

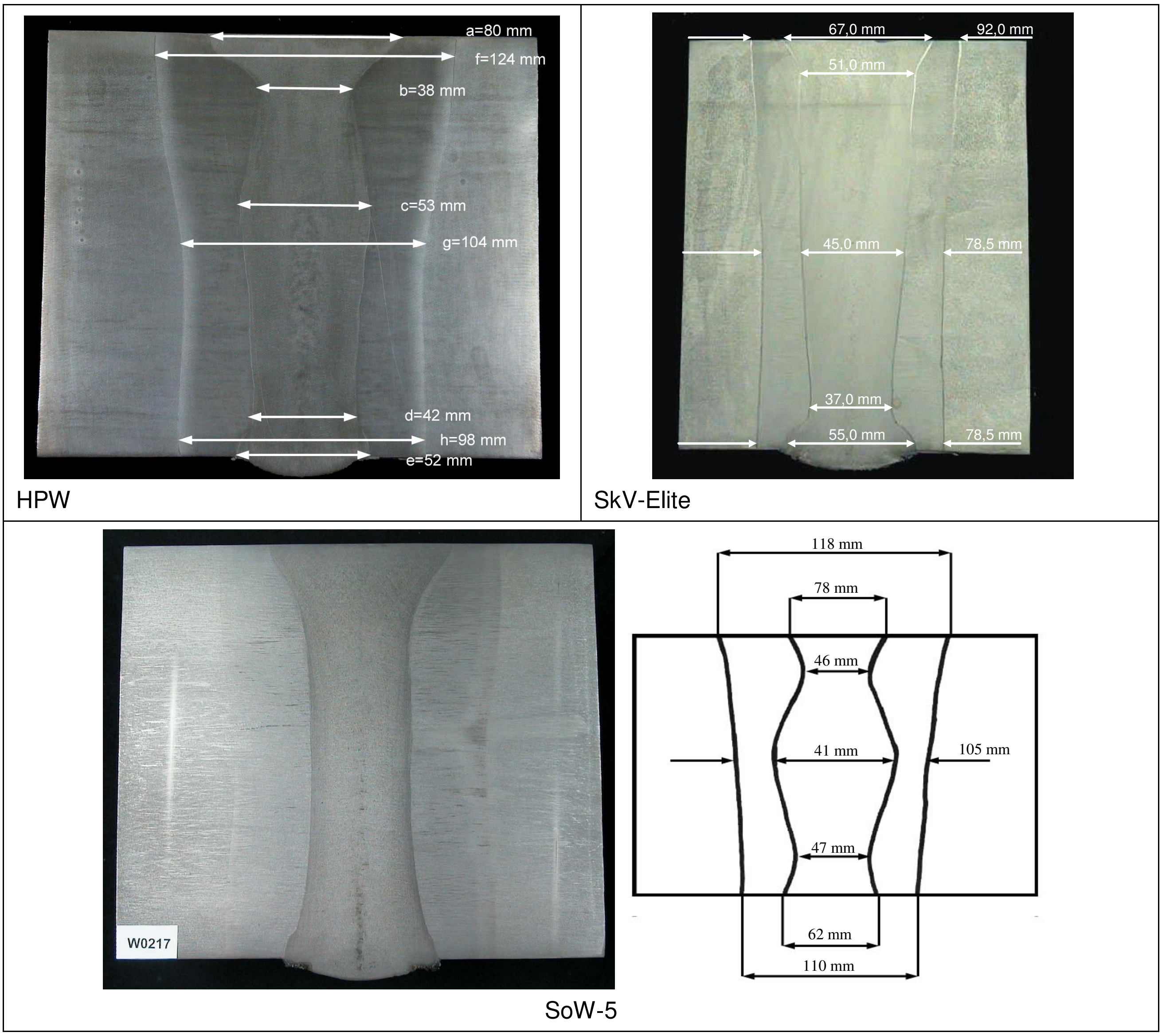


Figure 4 - Shape and Geometry of Different Aluminothermic Welds

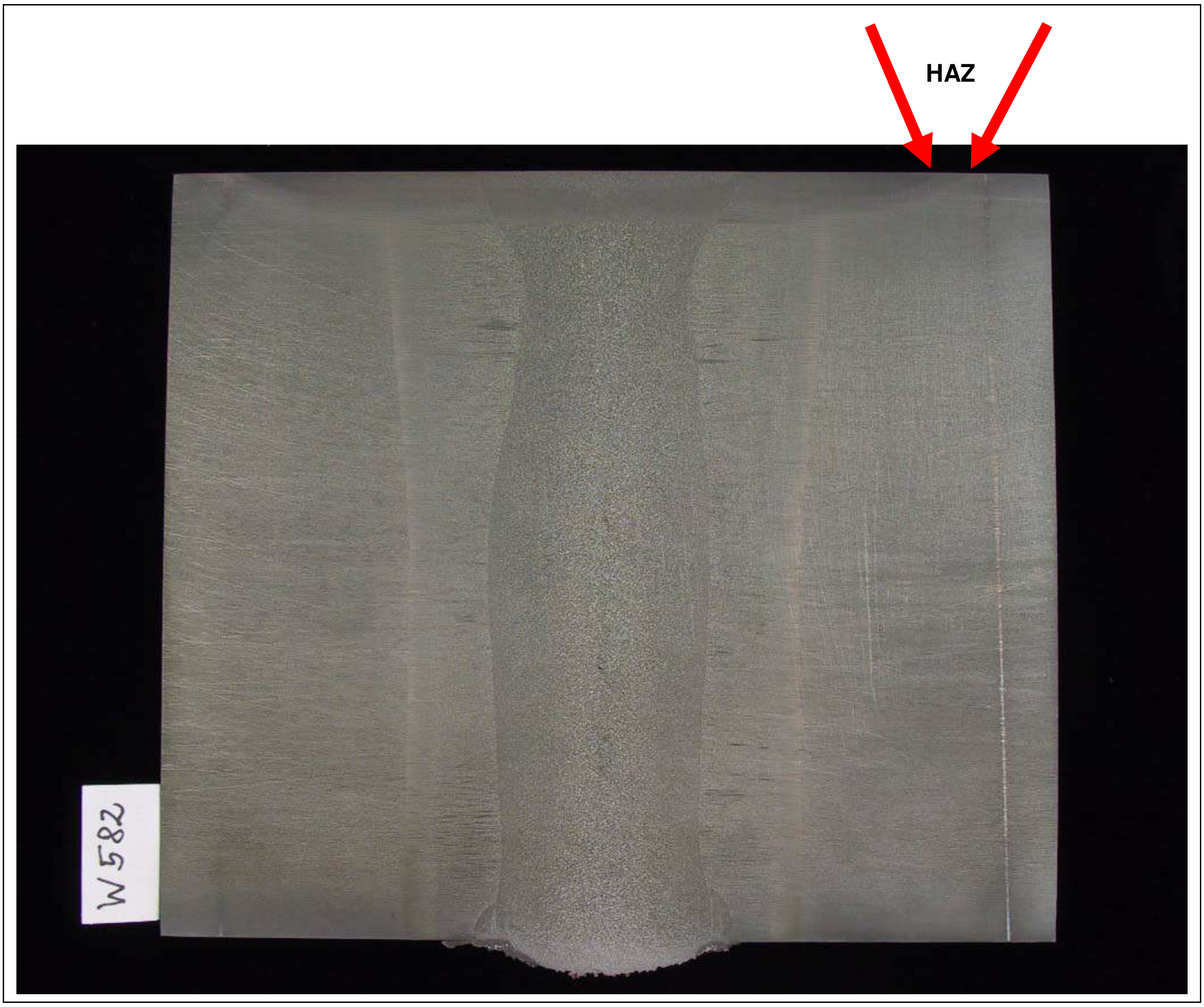


Figure 5 - Longitudinal Section of SkV-Weld With Additional HC-Treatment

As mentioned above, an additional heat treatment can be performed in order to modify the initial microstructure. This so-called HC-treatment causes the formation of a very fine pearlitic microstructure and an increase of hardness. However, this second heat treatment somehow covers the HAZ that has been created before, and a new HAZ will be formed at the borders from the area that is affected by the heat treatment.

Figure 5 shows a longitudinal section of a SkV-weld with this additional heat treatment. On the one hand the fusion line and the HAZ of the aluminothermic weld are clearly visible; on the other hand a dark shaded, crescent shaped area below the running surface becomes visible. This is the area where the heat treatment causes the formation of the fine pearlitic microstructure, and (indicated by the arrows) a second HAZ has been formed.

The additional heat treatment is superimposed to the heat treatment that was caused by the initial welding process, but as it can be seen in Figure 5 the location of the initial fusion line and the HAZ still remain visible in the longitudinal section.

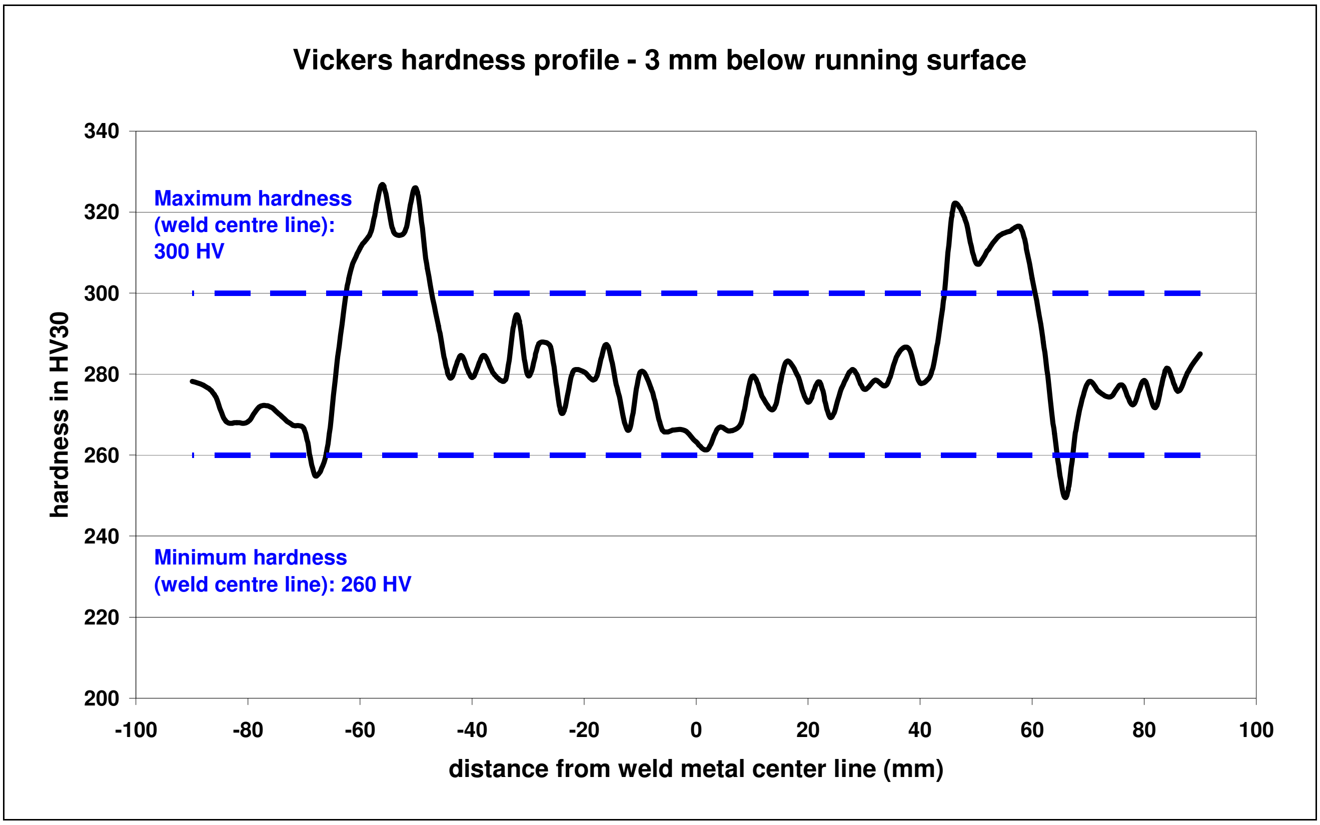


Figure 6 - Typical Hardness Profile of Aluminothermic Weld (Rail Grade R260)

Figure 6 shows a typical hardness profile of an aluminothermic weld. Here it can be seen that a hardness peak occurs at the transition from weld metal to HAZ followed by a drastic decrease of hardness in the HAZ. The change of hardness will determine the performance of the weld in a more distinct way than the exact width of the HAZ.

With regard to Flash Butt Welding a narrow HAZ with a width of e.g. 26 mm (see Table 2) represents a very narrow band that is affected by the welding procedure; but with regard to an aluminothermic weld the sum of HAZ and weld metal need to be regarded.

Based on the above given considerations in this project the HPW (high performance weld) welding procedure will be considered. As already indicated above, this welding procedure has not been chosen due to the formation of a very small HAZ.

This welding procedure has been introduced to weld mainly head hardened rails. A special alloying system allows achieving a weld with high hardness in the head and low hardness in the web and base of the weld. The reduced hardness of the base is linked to an improvement of fracture toughness in the base and web area. Thus, the integrity of a HPW weld and the susceptibility to crack growth under critical dynamic loads is better than a commonly used weld with the same high hardness all over the weld.

An HPW weld is therefore a quite innovative product because it enables to decouple the properties of head and base of the weld. The wear resistance and the resistance against rolling contact fatigue of the hard head can be combined with the higher ductility of the base of the weld.

4.2 HPW welding procedure


a)


b)


c)

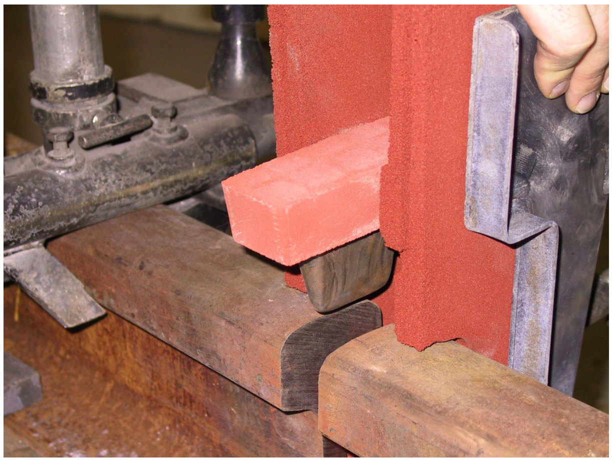

d)

Figure 7 - Schematic presentation of the HPW process

A high performance weld (HPW) is characterised by a distinct difference of hardness between head and base. The high hardness of the head is achieved by using a small container with alloying elements that is attached under the plug (Figure 7d). The welding process is given schematically in Figure 7a to c.Here it can be seen that the liquid metal reaches the container with alloying elements at a late stage of the casting process. The container dissolves and the alloying elements are released. A homogeneous distribution of the alloying elements in the head of the weld causes an increase of hardness. The required hardness level is dependant on the grade of the rail and can be controlled by the amount (or concentration) of alloying elements. For example for welding R350HT rails then a base portion Z90 (normally used for welding R260 rails) is used with the head being selectively alloyed to increase the hardness to match that of the parent rail head. Typical alloying elements that can be used to influence the hardness level are e.g. Vanadium and Carbon.

Typically, this welding procedure is used to weld head hardened rails of grade R350HT or 370LHT. Using a base weld metal with low hardness (e.g. corresponding to rail grade R260) the alloying systems allows achieving the hardness of R350HT or 370LHT rails in the head of the weld.

4.3 Properties of HPW weld

To demonstrate the properties of welds e.g. slow bend tests and hardness measurements are used. Table 3 shows results of slow bend tests of HPW welds manufactures with a base portion of Z70(used for welding R200 rail). The bend tests have been carried out in accordance with EN14730-1.

Rail grade / hardness (HB)	Mean fracture load (kN)	Mean deflection (mm)
R260 / 275	1440	19,5
R320Cr / 335	1420	13,0
R350HT / 350	1475	17,5

Table 3 - Results of Slow Bend Tests, 60E1 Rail

In Figure 8 and Figure 9 hardness distributions of a HPW weld are represented.

Figure 8 shows the hardness along the rail height of HPW compared to SkV. The SkV weld has a constant hardness of about 350 HB (“Z120” portion; hardness range: 330 HB – 370 HB) whereas the HPW weld shows a hardness of about 260 HB (“Z90” base portion; hardness range: 260 HB – 300 HB) in the base and web and the increased hardness of 360 HB in the head. Figure 9 gives a three-dimensional impression of the hardness distribution in a longitudinal section of the HPW weld. The characteristic hardness profile in longitudinal direction as well as the increased hardness of the head is represented in this figure.The correlation between hardness (or the increase of hardness) and the content of the alloying element Vanadium is given in Figure 10.

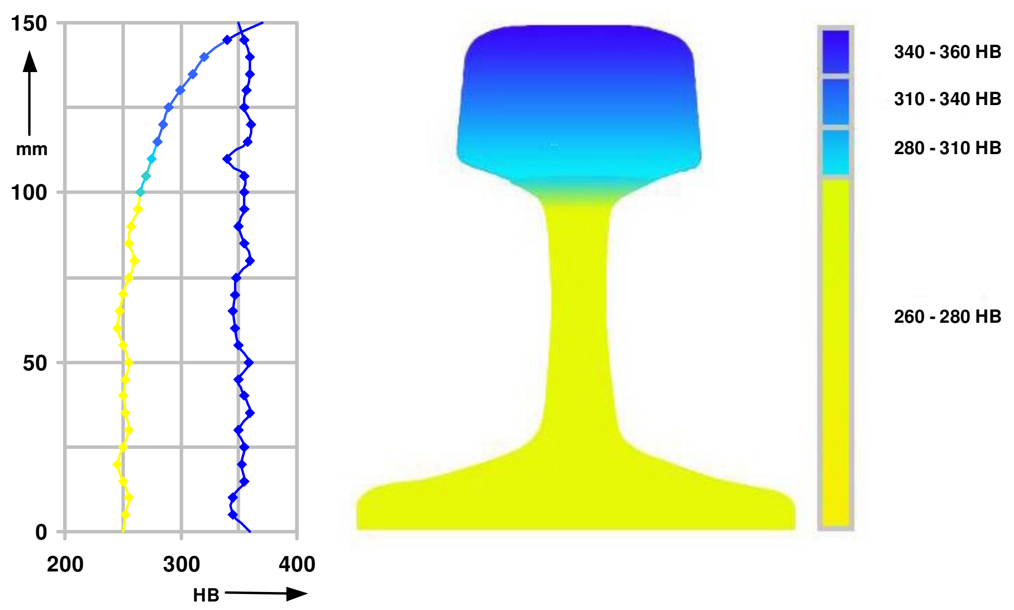


Figure 8 - Hardness Distribution – rail height; HPW compared to Z120 SkV

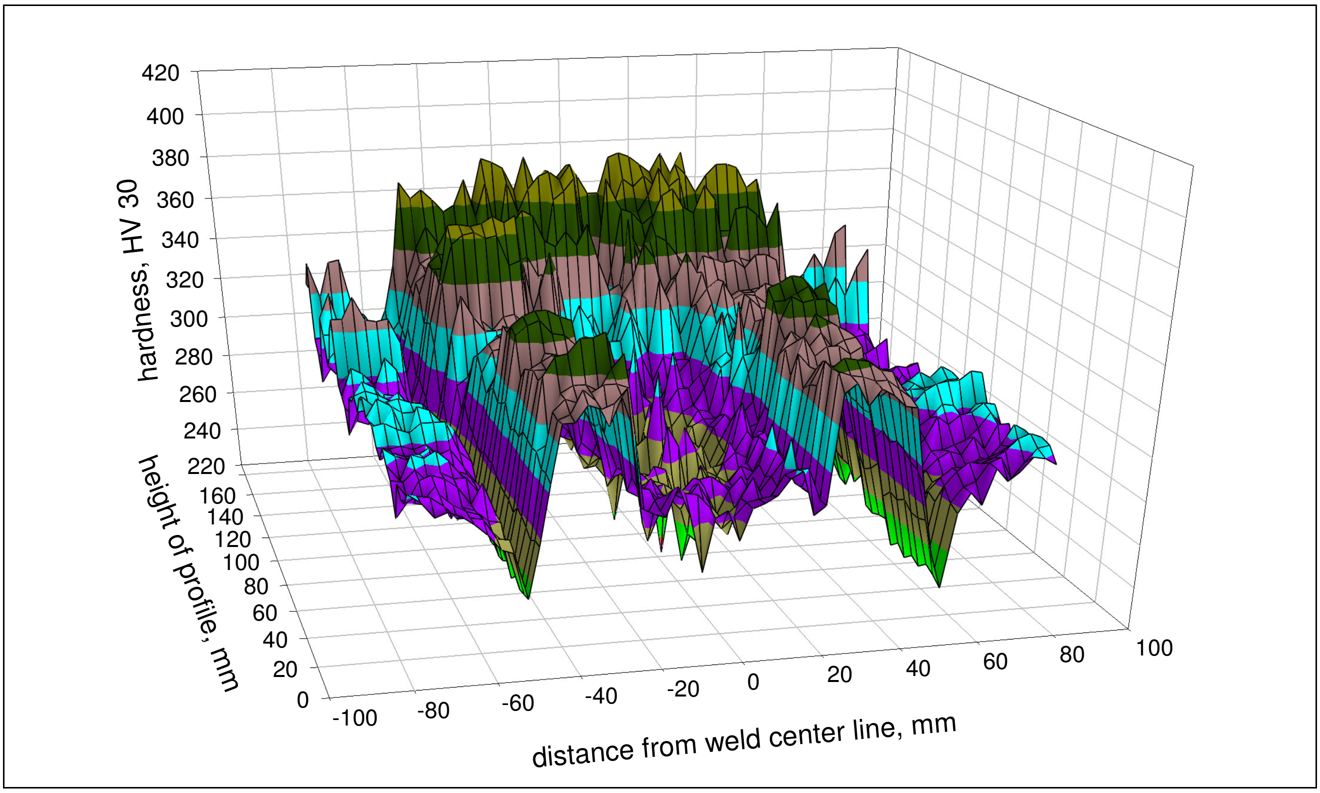


Figure 9 - Three-Dimensional Hardness Distribution of HPW weld – rail height vs. distance from weld centre

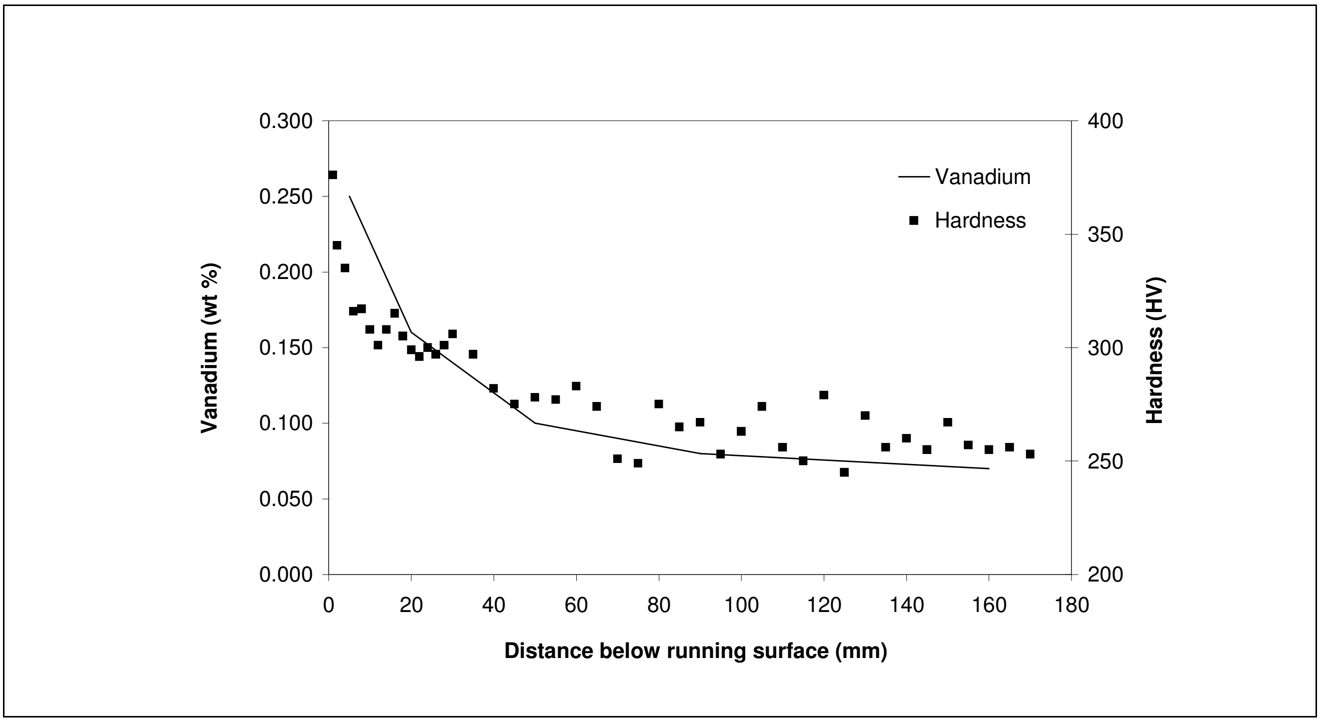


Figure 10 - Correlation between hardness distribution and vanadium content

5. Conclusions

5.1 Flash Butt Welding

1. The process parameters of flash butt welding that contribute towards the formation of the heat affected zone have been critically examined and optimised with the aim of significantly reducing the HAZ width towards the narrower end of that specified in EN 14587-1.
2. The process has been applied to all the commonly used rail steel grades and a number of rail sections.
3. The success of the new process has been demonstrated through the results obtained for Grade 350 HT, 60E1 rail. Data for bend strength, hardness profile, and bending fatigue strength all demonstrate full compliance with EN 14587-1.

5.2 Aluminothermic Welding

1. Aluminothermic welding processes have not been optimized up to now with the aim to minimize the width of the HAZ. Experience has shown that SkV-Elite is the welding process that creates the narrowest HAZ compared to the other aluminothermic welding processes from Elektro-Thermit GmbH & Co. KG.
   Regarding aluminothermic welding the preheating time (besides other preheating parameters such as gas pressure, positioning of the preheating burner, etc.) seems to be the process parameter that has the largest influence on the width of the HAZ. A very short preheating time of about 1.5 minutes combined with an optimized mould design results in the narrow HAZ of the SkV-Elite process. For the HPW process a longer preheating time of about 3.5 minutes is used and consequently the width of the HAZ slightly increases. The usage of longer preheating times will further lead to a broadening of the HAZ.
2. Due to the demand for a sufficient bonding between rail steel and weld metal a preheating process is always required for aluminothermic welding. As long as similar preheating parameters (e.g. short preheating times) are used the width of the HAZ cannot be reduced any more to a large extent.
3. The width of the HAZ cannot solely be regarded if assessing the service performance of an aluminothermic weld. Both the width of the weld and the width of the HAZ need to be considered with regard to the properties. The change of properties along the complete weld has to be controlled to optimize the service performance.
4. Within this project HPW has been chosen as welding process because of its innovative welding procedure, that a selective alloying technique allows decoupling the properties of head and base of the weld. The high wear resistance of a hard head can be combined with the higher ductility of a base with lower hardness.

6. Bibliography

6.1 Intellectual Property Rights (IPR)

The narrow HAZ weld development has been protected by means of a UK patent (Patent number GB 2403174, entitled "Steel Rails" was granted to Corus UK Limited on 15 November 2006).

6.2 Conformity with Flash Butt Welded Rail Specifications

The narrow HAZ FB development meets all the requirements specified in both the European (EN 14587 – 1:2007) and Network Rail (NR/SP/TRK111, August 2003) specifications for flash butt welded rails produced in a fixed depot.