Influence of Segregations and Hydrogen Flakes on the Mechanical Properties of Forged RPV Steels

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Abstract

In the frame of relevant 1970s/80s German research programs (e.g. FKS research program on component safety and others), many investigations on large forgings manufactured from Reactor Pressure Vessel (RPV) materials such as 20 MnMoNi 5 5 and 22 NiMoCr 3 7 have been performed. Lately, after ultrasonic testing hydrogen flakes in connection with segregation zones have been observed in a few RPV forgings. The earlier R&D programs contained a number of special heats, which covered a defined defect state (lower bound heats) with relevance to the recent observations of numerous UT indications in RPV forgings of two PWRs. Therefore, the results of these former research programs were now reviewed.

The studies included an evaluation of the effects of macro/micro segregations as well as hydrogen flakes on the mechanical properties. As part of the mechanical technological experiments Charpy impact tests in different orientations (e.g. L-T, T-L and S-T) together with fracture mechanics and large scale tensile tests were carried out in segregated and non segregated material zones. In this context the letters L,T,S indicate the longitudinal, transversal and short transverse (thickness) direction with respect to rolling direction of the forging axis. The first letter indicates the direction of the principal stress, while the second letter stands for the crack propagation direction [1]. Furthermore the irradiation behavior of segregated material regions was analyzed and compared to non segregated material regions.

Key results of these analyses indicate that in most cases upper shelf levels are lowered in segregated material parts compared to non segregated areas. In addition the segregations cause a larger scattering of impact energies. A high hydrogen content in combination with segregations has overall detrimental effects on the mechanical properties. However, there seems to be no specific segregation influence on the materials' irradiation reaction.

1 Introduction / Motivation

Due to recent findings in large RPV forgings there is a strong interest to assess the effects of macro/micro segregations as well as hydrogen flakes on the mechanical properties of RPV steels. A literature study based on the results of former German research programs has been conducted and this paper makes a short summary of the main findings.

2 Segregations and hydrogen flakes

2.1 Segregation zones and types in ingots

The occurrence of material inhomogeneities within ingots, which are used for the manufacturing of large RPV forgings cannot be fully avoided [2]. Especially within segregated areas of the ingot increased concentrations of inhomogeneities can be found, which cannot be removed by additional forging or heat treatments [2]. Figure 1 displays the segregation zones within an ingot [2]. Frequency, distribution and size of segregations depend on many factors such as type of steel, cast ingot form, cast conditions, cast procedures etc. [3]. Segregations are formed during the solidification process through enrichment of accompanying elements in areas, which solidify at last. The strongest segregated areas are located in the upper part and in the middle of the ingot, these parts as well as the bottom part of the ingot are discarded before shell forging. Outside the center area the reversed V-segregations or A-segregations (ghost lines) can be found, which are formed through interdendritic flows on the solidification front of the ingot with a tubular rise of the remaining heat [4]. At the bottom area of the ingot oxide inclusions are accumulated [5]. Further detailed information regarding the solidification of large ingots can be found in [6].

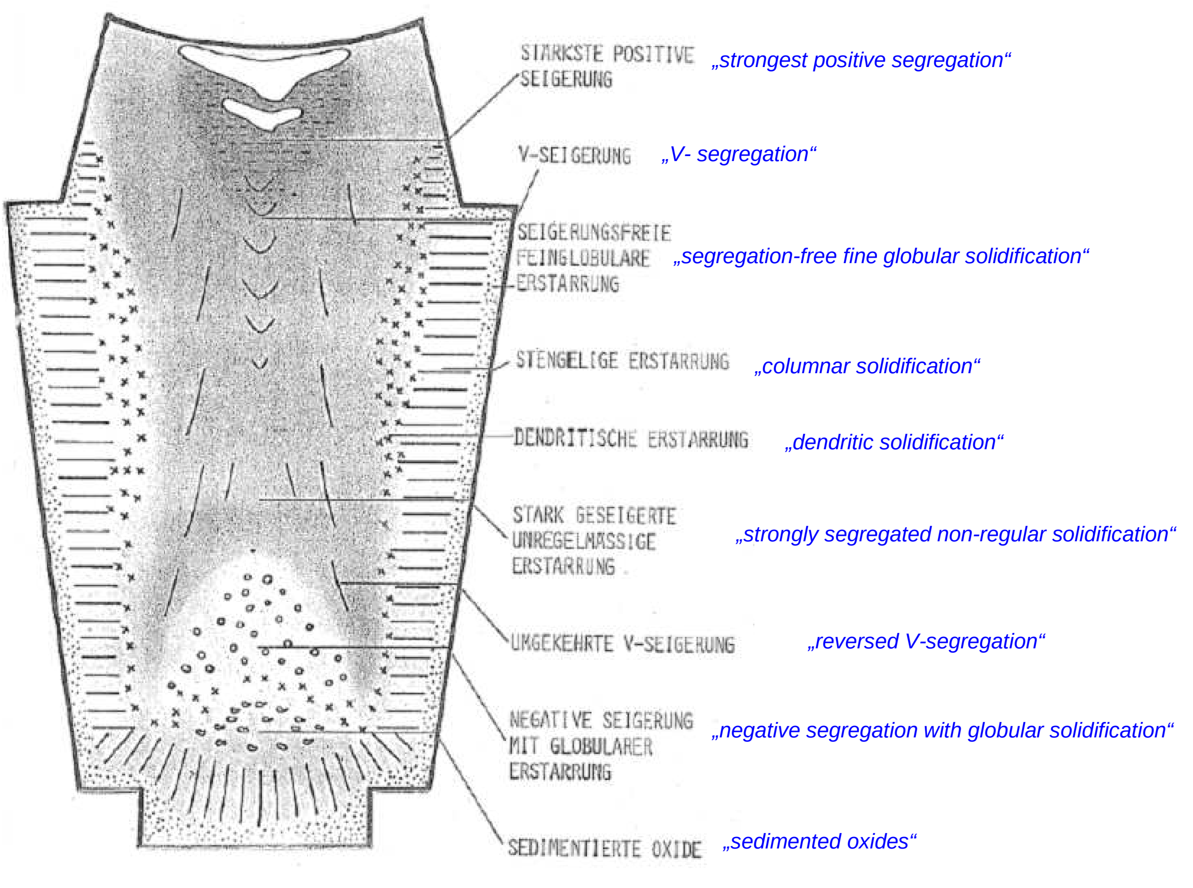


Figure 1: Sections of solidification and block segregations within an ingot [2]

In this context micro and macro segregations have to be distinguished: Micro segregations (or crystal segregations) are “heterogeneous material sections” with an irregular distribution of alloying elements together with impurities [7]. Micro-structural areas in a very close distance (~mm range) are either enriched (positive segregation) or depleted (negative segregation) with segregated elements (for vessels mainly Mo, Mn, Ni, S) [7]. They can be caused by a concentration difference on the phase boundary solid/liquid and based on the element diffusion in the solid/liquid state [6]. They appear in regions of primary solidified dendrites or globulites and the residual melt (enriched by accompanying elements) in the interdendritic area [6]. Decompositions within the crystal and temperature dependent concentration differences between the core and additional crystallized parts in the surrounding area are referred to as micro segregations as well [6]. On the other hand macro- or block segregations can be in the scale of whole ingots and are a consequence of a large scale material transport through convection currents [6]. The dimension of macro segregations can be in the cm or m range [6]. As mentioned, they can have a V-like or A-like shape and cannot be reversed or influenced by a heat treatment. They remain within the final component.

2.2 Flake crack formation in combination with hydrogen

The formation of hydrogen flakes depends on many factors [8]. Especially the presence of hydrogen in steels (or its remaining in the steel after manufacturing) can lead to a “delayed creation” of internal defects such as hairline cracks, fragmented cracks and flake cracks. Flake cracks appear after a certain incubation time at temperatures lower than 200°C and can be detected with analyses techniques such as ultra sonic tests. Influencing factors are mainly the hydrogen content within the material, (local) matrix toughness, segregations, (internal) stresses, size of forging, austenitic transformation, sulfur content, hardness increasing elements, oxides, purity of steel production and heat treatments [8].

The mechanism of flake creation can be described in the following way [8]: micro cracks are created at first as a consequence of residual or transformation stresses, which is promoted by segregations, hardness increasing elements and a high hydrogen content. The solubility of hydrogen in iron depends on the temperature, hydrogen partial pressure and alloy composition (see Figure 2 a)). Hydrogen creates so called interstitial compounds, it occupies gaps within lattice (which are larger in the γ -fcc than in the α -bcc modification). Hydrogen remains as an interstitial compound in a supersaturated state and cannot diffuse out of larger material blocks. It is kept longer in the γ –fcc or diffuses from α –bcc to the remaining γ –fcc, when only partially transformed, or towards so called hydrogen sinks (pores, defects, segregations…). Within pores a recombination of the atomic hydrogen to H_2 is possible. In this context the influence of positive and negative segregations (with increased/ decreased contents of carbon (and other elements)) is very unfavorable, because they exhibit differences in their transformation behavior [5]: Positive A-segregations stay austenitic for a longer time, than the surrounding already transformed ferritic area [6], which leads to the required transformation stresses and austenite favors hydrogen uptake due to the higher solubility (see Figure 2 a)).

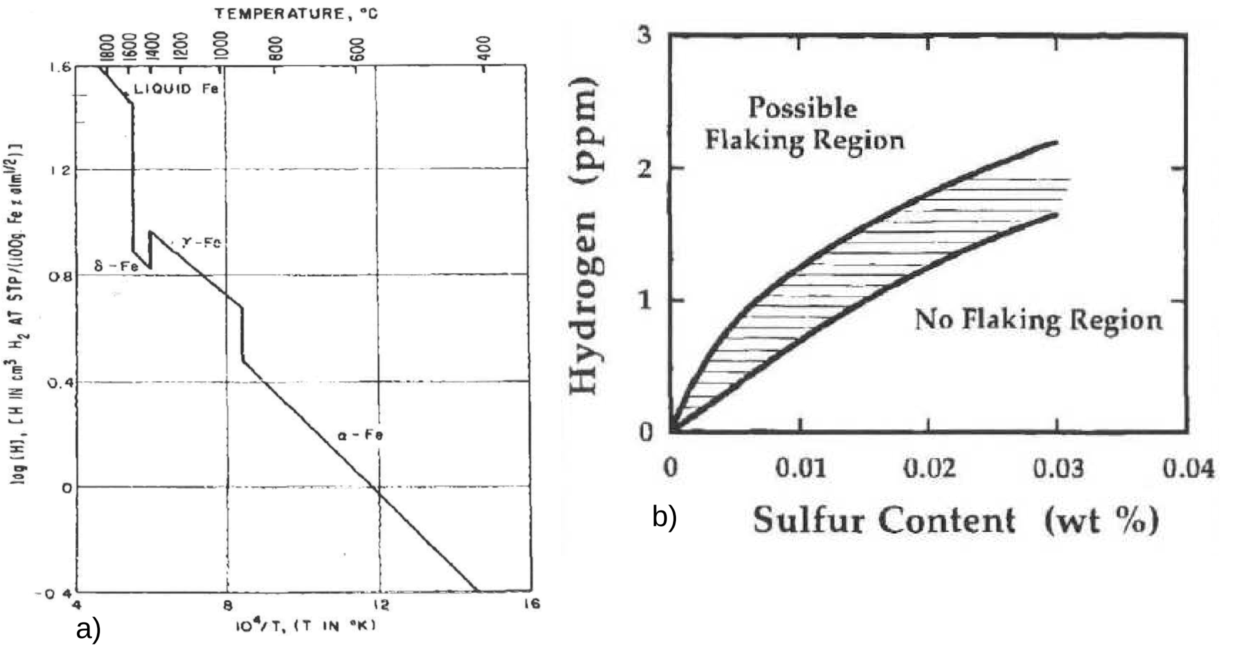


Figure 2: a) Solubility of hydrogen in liquid and solid iron; b) schematic depiction of the tolerable hydrogen content as a function of the sulfur content with regard to flake formation [8]

Furthermore material regions of positive segregations contain sulfidic inclusions (mainly MnS), which promote further hydrogen agglomeration and lead to an increase of the local hydrogen concentration as well as the partial pressure. Segregations can shift the solubility jump $\gamma \rightarrow \alpha$ towards lower temperatures.

Sulfur and sulfides play a decisive role in flake formation as well [8]: during the solidification process sulfur reacts with manganese and forms the mentioned MnS-inclusions. After thermo-mechanical treatments these inclusions can deform into elongated rods and become initiation centers for hydrogen induced cracks. MnS-inclusions have generally negative effects on the mechanical properties (e.g. fracture toughness). The lower the sulfide content, the more hydrogen will finally accumulate at the remaining MnS inclusions. As shown in Figure 2 b), the probability of flake formation for a steel with given hydrogen content increases with decreasing S-content. The consequence for steels with very low S-content is thereby, that too few MnS-inclusions exist to distribute the hydrogen at a “sufficient number” of accumulation centers [8].

A crack could then initiate at such inclusions, which act as a stress peak. Further dissolved elements decrease the necessary stresses for the crack initiation while hydrogen increases the stress level and weakens the matrix [8]. Hydrogen diffuses towards the free crack surface until the stress increase leads to a “hydrogen embrittled matrix”, which enables a further crack propagation [8]. Plastic deformation slows down or stops the crack growth temporarily, but hydrogen diffuses in this region further on and contributes to an additional destabilization and stepwise crack growth. It can take a couple of days, until the crack is fully formed. Hydrogen embrittlement is therefore essential for the creation of flake cracks. Summarized it can be stated, that a high hydrogen content increases the internal stresses, weakens the cohesion forces of the lattices and reduces the required surface energy for crack initiation [8].

Flake cracks (or segregation cracks) can even occur despite a lower hydrogen content (e.g. 0,8-1,2 ppm) [6], if a “hydrogen diffusion heat treatment” is not executed after the forging process. Such a treatment is time consuming and expensive and the detailed procedure is specific knowledge of the manufacturer. However, modern degassing techniques such as “double degassing” can significantly lower the heat treatment times [6].

3 Relevant research programs

In the 1970s and 80s several large research programs addressed the topic of hydrogen and/or segregation influence on the mechanical properties of RPV steels, such as

- BMI-TB SR 76 – investigation of the segregation behavior of the reactor material 20 MnMoNi 5 5 using a 180 ton ingot
- FKS – program (Research program on component safety)

In the following the most important results from these two research activities are used to evaluate the effects of segregations and hydrogen flakes on the mechanical properties of RPV steels.

3.1 BMI-TB SR 76

3.1.1 General

The R&D BMI-TB SR 76 project, ordered by the Federal Ministry of the Interior in 1981 and executed by MPA Stuttgart, investigated the steel 20 MnMoNi 5 5 in shape of a large 180t ingot due to its importance for operation in nuclear power plants [9]. The study contained a large amount of single results in several areas such as solidification process of large ingots, nature and size of defects within the ingot, extent of segregations and further defects within the ingot, as well as influence of segregations on mechanical – technological properties. Here the focus will lie only on this last item.

3.1.2 Tested parts, specimens and type of segregations

For evaluation of segregations the 180 ton ingot (unirradiated state) was segmented into several parts (see Figure 3). In this context the trepan 2B contained segregations while 2C was free of segregations. Charpy impact specimens (ISO-V specimens) have been taken out from the trepans 2B and 2C (middle and upper part) [9]. The specimens were orientated in radial and axial directions [9].

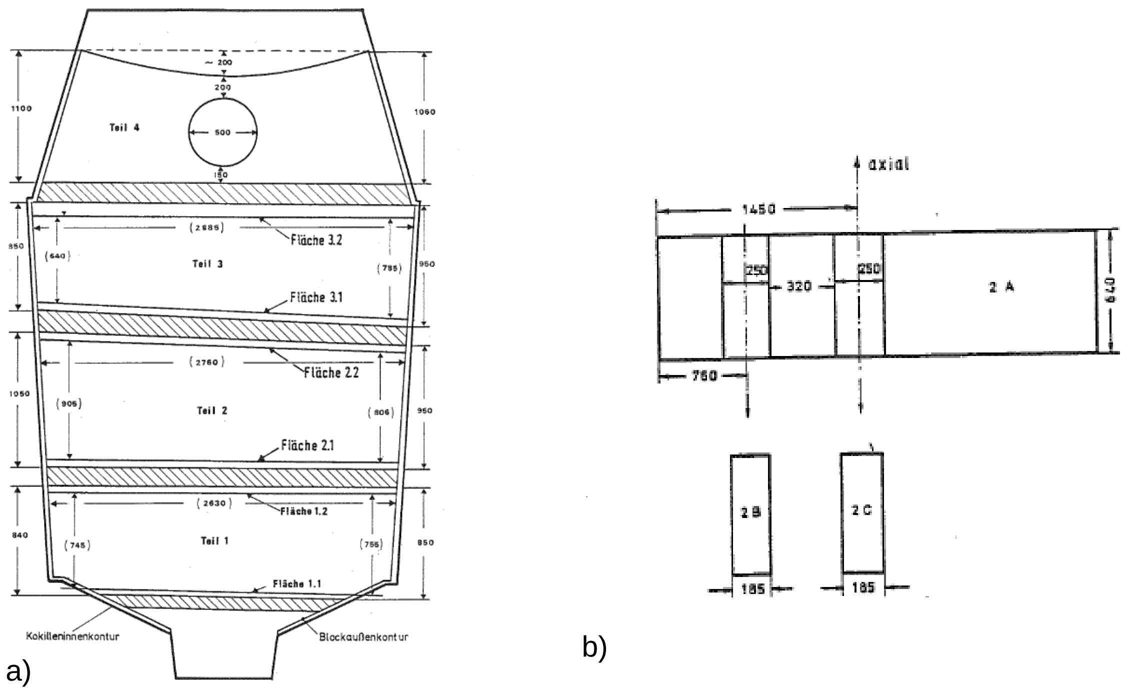


Figure 3: a) 20 MnMoNi 5 5 180 ton ingot, b) extracted trepans 2B and 2C from part 2 [9]

3.1.3 Results

The effect of such segregations on the impact toughness in dependence of the test temperature is shown in Figure 4 as an example. Av-T (lower bound) curves of the tests from the upper parts of trepans 2B (segregated) and 2C (non segregated) in radial direction are compared. A decrease of impact toughness in the segregated areas can be observed for the trepans 2B and 2C in Figure 4 where a decrease of upper shelf energy from ~120J to ~98J is depicted. The width of the Av-T curves' scatter bands is generally much larger for segregated areas due to the heterogeneous material state [9]. However, no clear dependency of the transition temperatures from segregations can be derived from this data [9].

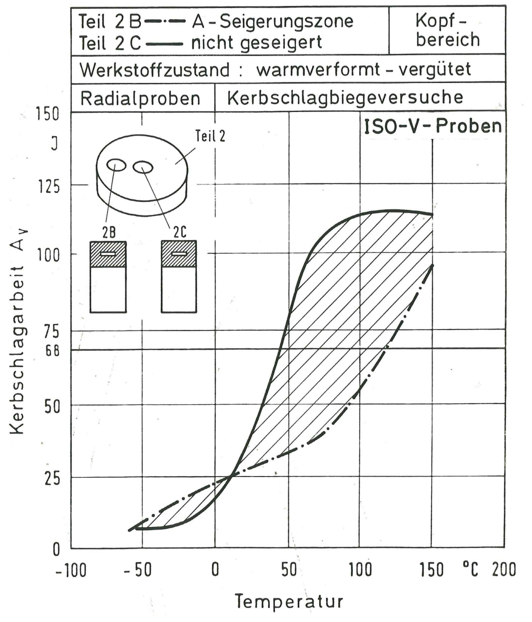


Figure 4: Comparison of Charpy impact tests (lower bound curves) [9]: from trepans 2B (segregated area) and 2C (non segregated area) in radial direction

3.2 FKS-Program on component safety

3.2.1 General

The R&D-program component safety (FKS) was designed in the frame of the "4th nuclear program of the Federal Republic of Germany" on behalf of the Federal Ministry of Research & Technology in 1975 and coordinated by MPA Stuttgart [10]. The set of tasks comprises production, operation and safety technology of components within light water reactors (LWRs). In addition to components within the "pressurized part" of the primary cooling cycle, FKS addresses relevant safety issues of reactor pressure vessels and other safety relevant non-nuclear pressure vessels including pipes. The three basic aspects of the program were [10]:

- Analyses of a material- and defect state following a defined production cycle
- Operational changes of the material- and defect state caused by the production
- State of safety technology – improvement of safety standards

3.2.2 FKS-heats

The main materials evaluated were the RPV steels 22 NiMoCr 3 7 and 20 MnMoNi 5 5 next to several other compositions, not discussed here. Generally heats were investigated, which cover a "reference-, limit- and cross limit-"state as well as withdrawn heats [11]. Among the many heats in FKS, the key heats addressing the effect of segregations/hydrogen are KS02, KS04 and KS07 A/B/C, which will be explained in the following. All heats corresponded to the requirements of VdTÜV-materials sheets, valid at manufacturing [11]. The chemical composition of the heats (cast analyses) is shown in Figure 5.

	Mass contents [%]								
Material	**Heat**	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
22 NiMoCr 3 7	**KS02**	0.19	0.2	0.93	0.008	0.006	0.5	0.56	1.29
	KS04	0.21	0.17	0.66	0.007	0.007	0.41	0.57	1.16
	KS07 A/B	0.30	0.29	0.63	0.021	0.021	0.46	0.99	0.74
	KS07C	0.30	0.30	0.99	0.02	0.011	0.52	1.03	0.75
		Al	**Cu**	**V**	**Sn**	**Co**	**As**	**N**	**H_2 (specification)**
22 NiMoCr 3 7	**KS02**	0.016	0.1	nd	0.007	0.014	0.028	0.014	-
	KS04	0.01	0.09	0.01	0.008	0.015	nd	nd	-
	KS07 A/B	<0.004	0.26	0.05	0.11	0.17	0.027	nd	> 2.5 ppm
	KS07C	0.005	0.26	0.01	0.009	-	0.022	nd	2.5 - 4.0 ppm

*nd: not determined

Figure 5: Chemical composition of FKS- heats KS02, KS04 and KS07 A/B/C (Cast analyses; the H_2 content is taken from the specification of the heats) [11]

The results of the non destructive testing for description of the interesting FKS-heats' defect states are summarized in Figure 6 [11].

Heat	**NDT-method**	**Results**
KS02 (Block)	US	- band of indications with dimensions of 450x~500mm in the whole cover flange ring - crack planes in L-T plane - largest single standard defect size KSR 13mm Ø - maximum of indications at KSR 2.5 Ø mm at 2 MHZ
	MP	- largest single crack length 20mm
KS02 (Plate)	US	no results
KS04	US	- area with indications within the tube sheet with the dimensions Ø 2500mm x 400mm thickness - crack planes in L-T orientation - largest single standard defect size KSR 14mm Ø - maximum of indications at KSR 3.5 Ø mm at 2 MHZ
	MP	- surfaces free of results; ground core indications with 1-5mm length
KS07 A/B	US	- 8 smaller indication fields in the middle of the slab
KS07 C	US	- large indication field in the middle of the slab - failure of back wall echo - areas close to surfaces are free of indications
	MP	- X-shape crack orienation on the front side of a blok from the slab middle - largest single crack length ~50mm

NDT: Non destructive test
US: Ultra sonic
MP: Magnetic powder
KSR: Kreisscheibenreflektor (engl. "Circular disk reflector")

Figure 6: Results of non-destructive tests of heats KS02, KS04 and KS07 A/B/C [11]

KS02

The heat KS02 was a PWR-cover flange ring made of the material 22 NiMoCr 3 7 for a 1300 MW_e PWR, which was withdrawn, after an ultra-sonic analyses revealed many indications in the middle section of the ring, while the edges did not contain segregations [11]. In the segregated zone the measured standard defect size had maximum KSRs (Kreisscheibenreflektoren = circular disc-shaped reflectors) in the range of 13 to 20mm. Further core- and fractographic analyses identified micro-/ and macro segregations and flake cracks, confirming the findings of the NDT-tests (see Figure 6) [11]. Before integration in the FKS-program some segments were annealed as a block, others were forged into plates and then annealed. After the forging the indications disappeared completely [11].

Irradiation of KS02

Neutron irradiation causes changes in the microstructure of materials during plant operations, which generally leads to an increase of strength and a reduction of toughness [12] [13]. For safety relevant analyses a fracture mechanics boundary curve is adjusted, based on a reference temperature RT_{NDT} and a transition temperature shift ΔT_{41}. This enables the determination of a safety margin towards the load paths (in the shape of normal operation as well as accidental conditions) for any point of operation. This procedure is based on the fracture toughness K_{IC}- and K_{IR}-curves, which are related to the RT_{NDT} (relative temperature: T-RT_{NDT}) as described in the American guidelines ASME III App. G. [14] and ASME XI A 4000 [15] and in the German KTA 3201.2 [16] standard. Based on the “material specific” reference temperature RT_{NDT} the fracture toughness curve can be shown in dependence of an absolute temperature scale, where an adjustment of the curve as a consequence of irradiation induced property changes is possible [17] [18] [19].

For specific irradiation tests the material KS02 was disassembled into two ingots with lengths of 1750mm (measured at outer circumference) [12]. KS02 (as base materials, BM) was irradiated in the reactors FRG-2 and VAK reactor to investigate the combined influences of segregations and irradiation on the mechanic al properties. For that purpose large capsules were designed and an irradiation temperature of 288°C was applied. The applied fluence range (E > 1 MeV) for the FRG-2 reactor was ~4,5E18 $n/cm^2 \leq \Phi \leq$ ~9,0 E19 n/cm^2 and for the VAK reactor ~2,0 E19 $n/cm^2 \leq \Phi \leq$ ~4,0 E19 n/cm^2. More details regarding the irradiation program can be found in [12] [13].

KS04

The heat KS04 (22 NiMoCr 3 7) came from a steam-generator tube sheet, which was withdrawn due to ultra sonic testing (UT)-signals (see Figure 6) resulting from a strongly segregated section within the tube sheet, which exhibited micro- and macro segregations as well together with micro-/macro cracks [11]. Again the “edge-zones” did not contain segregations. Cracks up to a length of 10mm and circular flake like “separations” up to a diameter of 12mm were found, which were attributed to the influence of hydrogen (hydrogen flakes). Flake cracks were found in segregation lines. Within their centers pores were located, which contained manganese sulfides [11].

KS07 A/B, C

The heat KS07 was manufactured as a slab to form a “lower bound” limit heat for the material 22 NiMoCr 3 7 with respect to low toughness and the formation of micro-/ macro cracks [11]. This state was achieved by a special chemical composition and modified manufacturing parameters. However, the first melt of this kind, KS07 A/B, had a too high sulfur content (see Figure 5), so that the final material contained too many sulfides and the hydrogen, as described in section 1.2, could agglomerate at too many sites [6]. Therefore an insufficient local H_2-concentration was obtained [6]. A further heat, KS07 C, had to be manufactured with a reduced sulfur content and a further increase of the H_2-content up to 4ppm as shown in Figure 5. This measure lead to the strong segregations together with hydrogen induced flake cracks, intended for investigation [6] [11].

3.2.3 Influence of segregations/hydrogen on the mechanical properties of KS02, KS04 and KS07 A/B/C (unirradiated state)

In terms of evaluating the mechanical properties of the FKS-heats Charpy impact tests with specimens in different orientations L-T, T-L and S-T have been executed (see Figure 7).

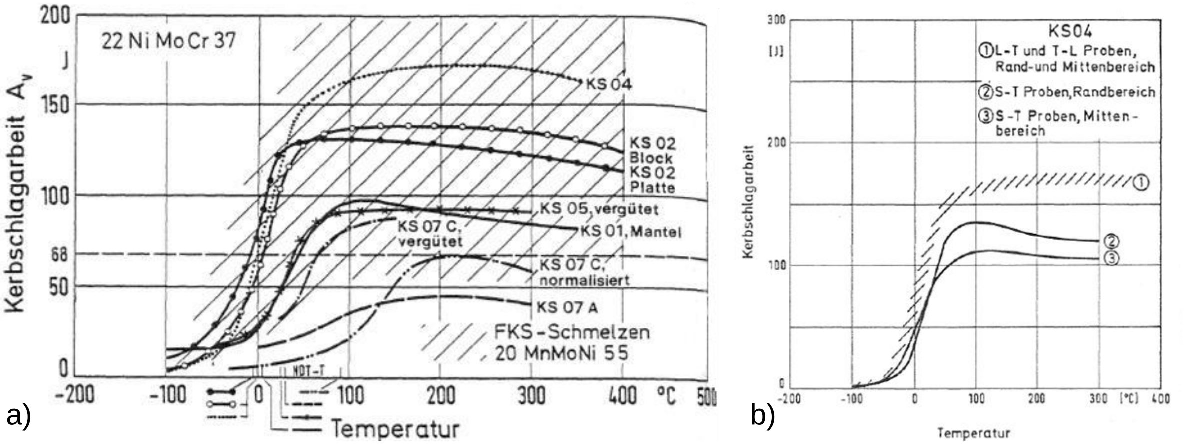


Figure 7: Impact energy – temperature curves (unirradiated state): a) of the FKS heats 22 NiMoCr 3 7 (T-L orientation); b) of KS04 edge and center area in L-T, T-L and S-T direction [11]

The specimen extraction was performed according to the ASTM Standard E 399 [20]. As can be seen in Figure 7 a) for the heat KS07 C, toughness values are relatively low with 90 J as upper shelf level for the tempered state [11]. The RT_{NDT} was 29°C for tempered KS07 C (for KS07 A no RT_{NDT} was determined). For the heats with a very flat increase of the Av-T curve in the transition area (e.g. KS07 C), RT_{NDT} was not determined with the NDT–temperature from drop weight tests according to ASTM E 208, but by the temperature obtained from the impact energy- and lateral extension curves according to ASME section III NB 2331 [11]. The toughness values of the other relevant heats KS02 (block and plate shape) and KS04 are in the upper area of the scatter bands and the RT_{NDT} values are considerably lower, however the specimens were taken from the non segregated edge section of both materials. Die NDT-temperatures of the 22 NiMoCr 3 7 FKS-heats are between -5°C and 90°C [11]. KS05 and KS11 are additional FKS heats, which will not be addressed in this contribution together with the 20 MnMoNi 5 5 heats, whose scatter bands are contained in Figure 7 a) as well.

Impact specimens from the heat KS04 (edge and middle section of the steam generator tube sheet) were machined in three orientations (L-T, T-L and S-T) (see Figure 7 b)) [11]. The Av-T curves from L-T and T-L orientations do not show much difference (narrow scatter band). The curves from the S-T "thickness" direction are displaced to ~20K higher temperatures, the upper shelf levels of the "edge-area" are around 130J and of the "center area" of ~110J. This corresponds to a ~24% / ~36% decrease in comparison to the curves in longitudinal and transverse direction, which reach ~172J [11].

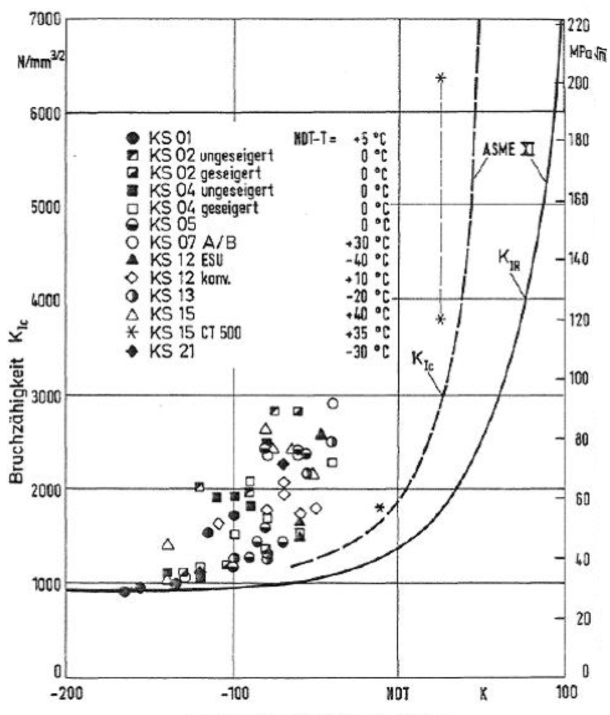
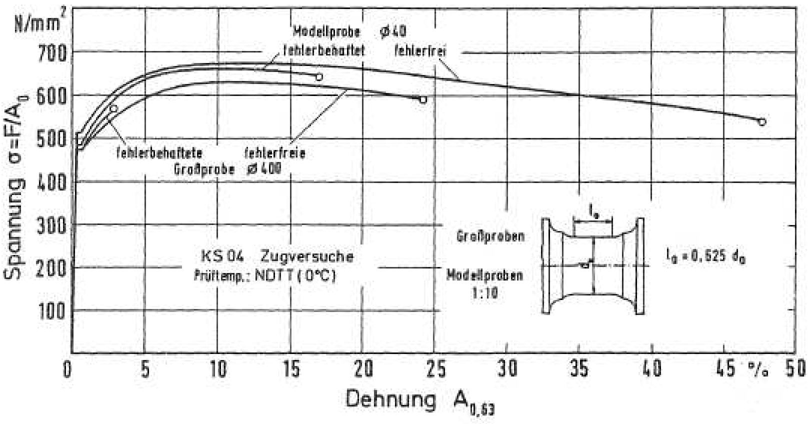


Figure 8: Critical fracture toughness values of FKS-heats in relation to the NDT-temperature [11]

Fracture toughness tests were performed with C-(T) specimens of different sizes. Figure 8 shows the critical fracture toughness K_{IC} in relation to the NDT-temperature for a set of FKS heats [11]. It can be seen, that all critical fracture toughness values of the FKS-heats have a rather large margin (40-80K) towards the K_{IC}- and K_{IR}-curve according to ASME Section XI, App. A. (except the CT 500-specimens from KS15, not treated here) [11]. This conclusion is explicitly valid for the heats KS02, KS04 (for which toughness values in the segregated and non segregated state are displayed) together with KS07 A/B (lower bound material) [11].



Tensile tests KS 04		
Model specimen Ø 40 mm		
Value	Material region	
	non-segregated	segregated
A_{l0} [%]	47,6	17,2
Z [%]	50,1	17,2
σ_{max} [N/mm²]	670,7	666,5
Large tensile specimen Ø 400 mm		
Value	Material region	
	non-segregated	segregated
A_{l0} [%]	23,8	2,5
Z [%]	28,5	3,6
σ_{max} [N/mm²]	630	566,6

Figure 9: Stress-/ strain curves from tensile tests with large and model specimens from the material KS04 (including and excluding defects) together with characteristic test values [21]

Figure 9 shows the stress/strain curves and the characteristic values (maximum stresses σ_{max}, elongation at fracture A_{l0} and necking Z) from tensile tests of the material KS04. The according samples, large round specimens with a diameter of 400 mm together with another model specimen (Ø 40mm), were taken from the non segregated edge-regions and segregated center-regions for comparison of both states [21]. The large tensile specimens of KS04 tested at 0°C showed, that at low toughness (lower shelf area) a strong reduction of deformation capacity and reduction of area takes place (from A_{l0} =23,8% and Z=28,5% (non segregated material) to 2,5% and 3,6%, respectively (segregated material)) [21]. Therefore a level of only ~10% of the “defect free” material could be obtained and the segregated material specimen broke before reaching the uniform elongation of the non segregated material (at around ~11%). The model specimen exhibited a higher deformation capability (A_{l0} =17,2% and Z=17,2%) in the segregated state compared to the large specimen, however it still broke at a lower elongation than the non segregated material. The maximum stresses were not much different. An important result for the KS04 material was, that the specimens, which included segregations and flake cracks, withstood loads higher than the material’s yield strength $R_{p0,2}$=452 N/mm² (for the segregated and non segregated case), despite the severe reductions of the specimen’s cross section [21].

3.2.4 Irradiation behavior of KS02 (segregated and non segregated state)

To display the influence of segregations on the irradiation behavior of KS02 Figure 10 a) contains it’s transition temperature shifts (ΔT_{NDT} and ΔT_{41}) while b) shows it’s adjusted reference temperature $RT_{NDT(j)}$, both in dependence of the neutron fluence (E > 1 MeV) as well as in the segregated and non segregated state [13]:

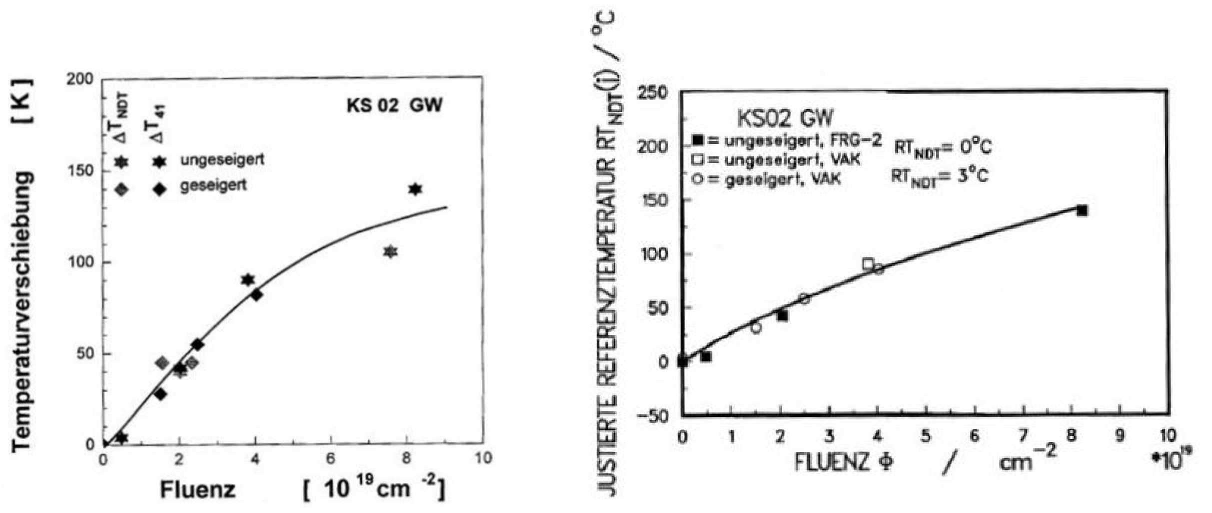


Figure 10: a) Transition temperature shift of KS02 (segregated and non segregated areas) in dependence of fluence; b) adjusted reference temperature of the material KS02 (segregated and non segregated) in dependence of the neutron fluence [13]

Figure 10 a) shows, that the increase of ΔT_{NDT} and ΔT_{41} for KS02 is very similar for both, the segregated and non segregated material regions for rising fluences [13]. Drop weight tests lead to NDT-temperatures of 0°C in both states, which finally results in a RT_{NDT} temperature of 0°C for the non segregated and 3°C for the segregated material region Figure 10 b). It can be seen that the adjusted reference temperature is below 100°C up to a fluence of 5,0 E19 n/cm² and that it has a value of ~140°C at the highest accumulated fluence of 8,25 E19 n/cm². From these data no influence of the segregations on the $RT_{NDT(j)}$ can be observed [13].

4 Summary and conclusion

This contribution gave an overview on 1970s/80s German research programs (e.g. FKS research program on component safety), where many investigations on large forgings manufactured from RPV materials (such as 22 NiMoCr 3 7) have been performed. Among those investigations, an evaluation of the effects of macro/micro segregations as well as of hydrogen flaking on the RPV's structural integrity was included. In addition, mechanical tests (like K_{Ic}, charpy impact testing in different orientations, tensile testing) and comparisons of segregated and non segregated zones within several different forgings were performed. Furthermore the irradiation behavior of segregated areas was addressed. From these findings following conclusions can be drawn:

- The solidification process of large ingots proceeds in a dendritic way with different concentrations on the solid/liquid phase boundary. These concentration variations promote the formation of micro segregations, which are "heterogeneous material sections" with an irregular distribution of alloying elements in close distance (cm or mm range). Macro segregations require an additional “macroscopic mass transfer” (convection flow) of enriched melt to be formed and lead to much larger concentration differences within the ingot.

- Flake crack formation in combination with hydrogen depends on a complex interaction of many factors such as hydrogen content in the material, matrix toughness, segregations, local stresses, and transition behavior. In addition the sulfur content plays an enormous role: if the amount of sulfur is too low, too few and too small sulfide inclusions remain, so that the hydrogen cannot be distributed at a sufficient number of sinks, which can locally create the critical conditions for flake cracks.

- In segregated material parts, impact energy values exhibit a large scattering, which is mostly higher than in non segregated materials. In most investigated cases, USE levels are lowered in segregated material parts compared to non segregated material parts.

- The curve enveloping all critical fracture toughness values of the FKS heats in relation to the according NDT-temperature have a rather large margin of 40K to 80K towards the K_{IC}- and K_{IR}-curve according to ASME Section XI, App. A. Based on the investigated data, no pronounced influence of the segregations on the fracture toughness properties was detected.

- KS04 impact specimens tested in S-T orientation resulted in slightly higher T_{41} temperatures compared to the L-T and T-L orientation for both the segregated middle section and the non segregated edge zone. While the USE of the segregated and non segregated zone is rather similar in L-T and T-L orientation (~172J), there is a 24-36% decrease of USE in S-T direction to ~130J for the non segregated zone and to ~110J for the segregated region.

- KS04 tensile tests (with large 400mm tensile samples) lead to a strongly reduced deformation capacity and reduction of area (KS04: A_{lo} =23,8% and Z=28,5% (non segregated material), down to 2,5% and 3,6%, respectively (segregated material, containing flake cracks). However, despite this lower deformation capacity, even the segregated KS04 versions withstood a higher maximum load at fracture (KS04: σ_{max}~566,6 N/mm^2) compared to both materials’ yield strengths (KS04, segregated and non segregated state: $R_{p0,2}$~452 N/mm^2).

- The increase of ΔT_{41} (including ΔT_{NDT}) is similar between segregated and non segregated KS02 material regions at increasing fluence: (f.e. at Φ=2,04E19 cm^{-2} ΔT_{41} is 42°C (no segregations) and at Φ=2,49E19 cm^{-2} ΔT_{41} is 49°C (segregations)).

The reviewed data have shown, that segregations may decrease the USE, however a drop below 68 J is only expected for very strong segregated „lower bound" materials like KS07. In this context it has to be stated, that the heats KS07 A/B/C were deliberately manufactured as "lower bound" materials to study the detrimental effects of a high hydrogen content in combination with segregations on the mechanical properties. A heat like KS07 A/B/C would never be used in a RPV. On the other hand no significant influence of segregations on ΔT_{41} and RT_{NDT} was found since the increase of $RT_{NDT(j)}$ with increasing fluence is not much different for the segregated material compared to the non segregated material. This indicates that the segregations may have an impact of the initial unirradiated state but no impact on the irradiation behavior itself. Furthermore, it could be shown that applying the RT_{NDT}-concept even to segregated base materials yields to significant safety margins with respect to the ASME "lower bound" K_{Ic}-curve.

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