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Recent advances in the understanding of the role of vanadium carbonitride precipitation to improve surface edge cracking on continuous casting of blooms

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Abstract. This study aims in combining the material properties and numerical modelling techniques through practical application to provide understanding of surface edge cracking caused by V(C,N) precipitation to enhance the yield of the continuous bloom caster at ArcelorMittal Duisburg. The investigation for this work is carried out on three different micro-alloyed steel grades; one of them being the most crack sensitive 20MnV6. A process model is used which calculates the solidification process of the strand to design an optimum cooling strategy. Therefore, two cooling patterns are employed for the steel grade 20MnV6. Reduction of area values of the steel grades 20MnV6, 27MnSiVS6 and 38MnSiVS5 evaluated from hot tensile tests using a Gleeble simulator have been used as an indication in assessing steel's cracking behaviour. Further precipitates have been analysed by SEM at ArcelorMittal. These laboratory results suggest that precipitation kinetics of V(C,N) influences the crack sensitivity of the micro-alloyed steel. The software MatCalc[®] is used to simulate precipitation for process parameters of continuously cast blooms at Arcelor Mittal Duisburg as well as the parameters of the Gleeble experiments. From these simulations the Zener pinning force (ZPF), resulting from V(C,N) particles on grain boundaries, is evaluated which can be used as a measure for the crack sensitivity. Using the values of the ZPF it is possible to identify the set of casting parameters of the steel grade 20MnV6 which lead to the minimum crack intensity on the surface of the blooms. Moreover it is possible to make a ranking list with respect to the ductility drop occurring in the Gleeble experiments for the analysed steel grades. The proposed statement is an issue for a continuing investigation of precipitation modelling.

1. Introduction

Transverse edge surface cracking is a common long-standing problem in continuous casting which has been studied for decades and understanding is a still challenging task for steel producers. This review describes the control of the kinetics of V(C, N) precipitation resulting in the second ductility trough in the austenitic temperature range from 800 °C to 1200 °C of the investigated steels and eliminating the



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edge cracking during straightening operations in the bloom casting. The investigation for this work is carried out on three different vanadium containing micro-alloyed steel grades.

The SMS group developed a process model X-Pact® Solid Control (former DSC® Dynamic Solidification Control) which calculates the solidification process of the strand and controls the various zones of the secondary cooling system [1]. An optimum cooling strategy depending on the temperature range of low ductility of each steel has to be designed to prevent transverse crack formation. Therefore, according to the experience of the casting practice at ArcelorMittal Duisburg two cooling patterns are employed for the steel grade 20MnV6. Reduction of area values of the steel grades 20MnV6, 27MnSiVS6 and 38MnSiVS5 from the hot tensile tests using the thermo-mechanical simulator Gleeble HDS V-40 has been used as an indication in assessing steel's cracking sensitivity. Further precipitates have been analysed by SEM at ArcelorMittal. These laboratory results suggested that precipitation kinetics of V(C,N) influences the crack sensitivity of the micro-alloyed steel.

Grain boundary precipitates are generally detrimental to ductility because they promote void formation during grain boundary sliding. When grain boundary sliding in austenite is active as a process of plastic deformation, micro-alloy particles at the austenite grain boundaries will encourage the development of intergranular failure, leading to increased steel brittleness. Large volume fractions of fine precipitates are likely to increase strength and refine the grain size, but they also reduce the ductility of the steel owing to a more effective pinning action of grain boundaries, allowing more time for crack nucleation [2-5].

The thermo-kinetic software MatCalc® is used for simulating the different casting process parameters as well as the parameters of the Gleeble experiments. From these simulations the Zener pinning force (ZPF) resulting from V(CN) particles on grain boundaries, is evaluated which can be used as a measure for the crack sensitivity.

The hindrance of grain boundary migration by precipitates due to a back driving force on the grain boundary is known as Zener pinning [6]. The Zener pinning force characterises the particle drag to inhibit the grain boundary migration by taking into account the volume fraction and also the size of the precipitates. The respective retarding force (ZPF) is expressed by

$$ZPF(k, i) = \frac{3}{2} \gamma \sum_i \sum_k \frac{f_{k,i}}{r_{k,i}}$$

where f is the volume fraction of the particles, r the mean precipitate radius, γ the grain boundary energy, i is to account for the different precipitate types and k the number of size classes [7]. In technical applications, the presence of precipitates resulting in Zener pinning is used to control the grain growth during heat treatment and thermo-mechanical processing to achieve better mechanical properties [7-8].

In the temperature regime of continuous casting, creep is the predominant effect of plastic deformation reducing stresses arising from mechanical loading and shrinkage. In case that the volume fraction is large and the size of the precipitates is small the ZPF is maximised. These conditions lead to a reduction of creep deformation (grain boundary sliding) and thus reduce the ability to compensate external stress by plastic deformation. In other words the material becomes brittle and the crack susceptibility increases. Therefore, we propose the Zener pinning force to characterise the crack susceptibility in the second ductility trough which is caused by the precipitates.

Using the values of the ZPF it is possible to identify the set of casting parameters of the steel grade 20MnV6 which lead to the minimum crack formation on the surface of the blooms. Moreover it is possible to make a ranking list with respect to the ductility drop occurring in the Gleeble experiments employing the values of the ZPF for the analysed steel grades. The proposed statement is an issue for a continuing investigation of precipitation modelling.

2. Simulation data

The thermo-kinetic simulations were performed with the MatCalc software, version 6.00 release 0.256 using the thermodynamic database mc_fe_2.059.tdb and kinetic database mc_fe_v2.011.ddb. In the simulations, the choice of the type of nucleation sites determines the number of potential nucleation sites

in the evaluation of the precipitate nucleation rate. The nucleation site for the V(C,N) precipitate phase at austenite grain boundary was defined according to the SEM fracture surface observations and EPMA investigations at ArcelorMittal previously presented in the paper from Leuschke et. al. [9]. Since the aim of the present paper is not the calculation of grain growth, the grain boundary energy was set to 1 J/m² in the simulations.

The simulations of precipitation kinetics for the as-cast material should not be carried out with the nominal compositions of steels due to micro-segregation. Scheil-Gulliver simulations are performed to estimate the segregation of the alloying elements in the interdendritic spaces and the phase fractions of primary precipitates during solidification. The nominal compositions of the steels are given in Table 1. Back diffusion of the fast diffusing elements carbon and nitrogen as well as the peritectic transformation are taken into account. The interdendritic compositions for which the precipitation simulations were conducted are evaluated from the micro-segregation simulation at a fraction of solid of 0.97 [10].

Table 1. Chemical composition (wt.-%) of the investigated steel grades

	C	Si	Mn	P	S	Al	N	Ti	V	Nb
20MnV6	0.220	0.440	1.580	0.015	0.030	0.020	0.021	0.003	0.180	-
27MnSiVS6	0.289	0.060	1.430	0.014	0.024	0.014	0.018	0.013	0.088	-
38MnSiVS5	0.375	0.565	1.355	0.013	0.068	0.026	0.015	0.002	0.099	0.003

The precipitation kinetics which are based on the temperature histories are calculated for two cases. For the first case, the simulation of the precipitation kinetics of V(C,N) on grain boundaries (gb) is performed for the temperature profile of the Gleeble experiments. For the second case of simulations, simplified surface edge temperature profiles for two cooling patterns of the continuously cast blooms at ArcelorMittal Duisburg via the thermal process model are applied. The two cooling strategies have been adapted to the temperature-dependent ductility drops especially during unbending to prevent transverse edge cracking on the bloom surface. Thermal simulations and temperature measurements have shown that the austenite-ferrite transformation does not take place at the edges of the bloom within the strand guide. The calculated A_{e3} temperature of the interdendritic composition of the three steel grades is lower than 790 °C which is below unbending temperature. Therefore, the kinetic simulations are performed by only accounting for the V(C,N)gb precipitation within the austenitic domain without consideration of the austenite-ferrite transformation which can be detrimental to ductility (third ductility trough).

3. Hot ductility curves

The plots of experimentally determined reduction of area (RoA) values against test temperatures for all steels examined in the present work are shown in figure 1. Over the whole temperature range the hot ductility is slightly decreased to values about 70 % which might be attributed to the formation of manganese sulphide in the solid. MnS precipitation in the solidification interval will produce coarse precipitates which should not significantly affect hot ductility. Of all the steels, 38MnSiVS5 exhibits the best ductility in the temperature range of 1000 - 950 °C followed by 27MnSiVS6 and 20MnV6. Due to the falling temperature a decrease in the RoA values is observed between 900 and 800 °C for steel 38MnSiVS5 but it exhibits higher values compared to the other investigated steel grades. It is therefore assumed to be less susceptible to cracking during unbending. The steels 20MnV6 and 27MnSiVS6 show a similar hot ductility behaviour with little variations in RoA values especially in the temperature range of the unbending process.

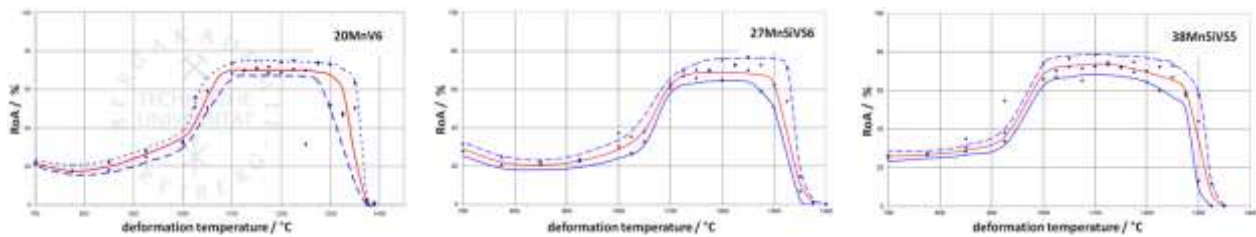


Figure 1. Hot ductility curves of the examined steels.

4. Results of thermo-kinetic simulations

4.1. Thermo-kinetic simulation of Gleeble curves

Results of thermo-kinetic simulations for V(C,N)gb precipitates in steel 20MnV6 are summarized in figure 2, showing the volume fraction, number density, size and the resulting Zener pinning force for a Gleeble temperature profile as used in the simulations. A particle volume fraction of 10^{-7} at the grain boundaries was suggested to be enough to obtain the predicted precipitation start temperatures. At 963 °C, precipitation of V(C,N)gb starts in steel 20MnV6 and at the same time the Zener pinning force starts to increase due to continuous nucleation of new fine precipitates.

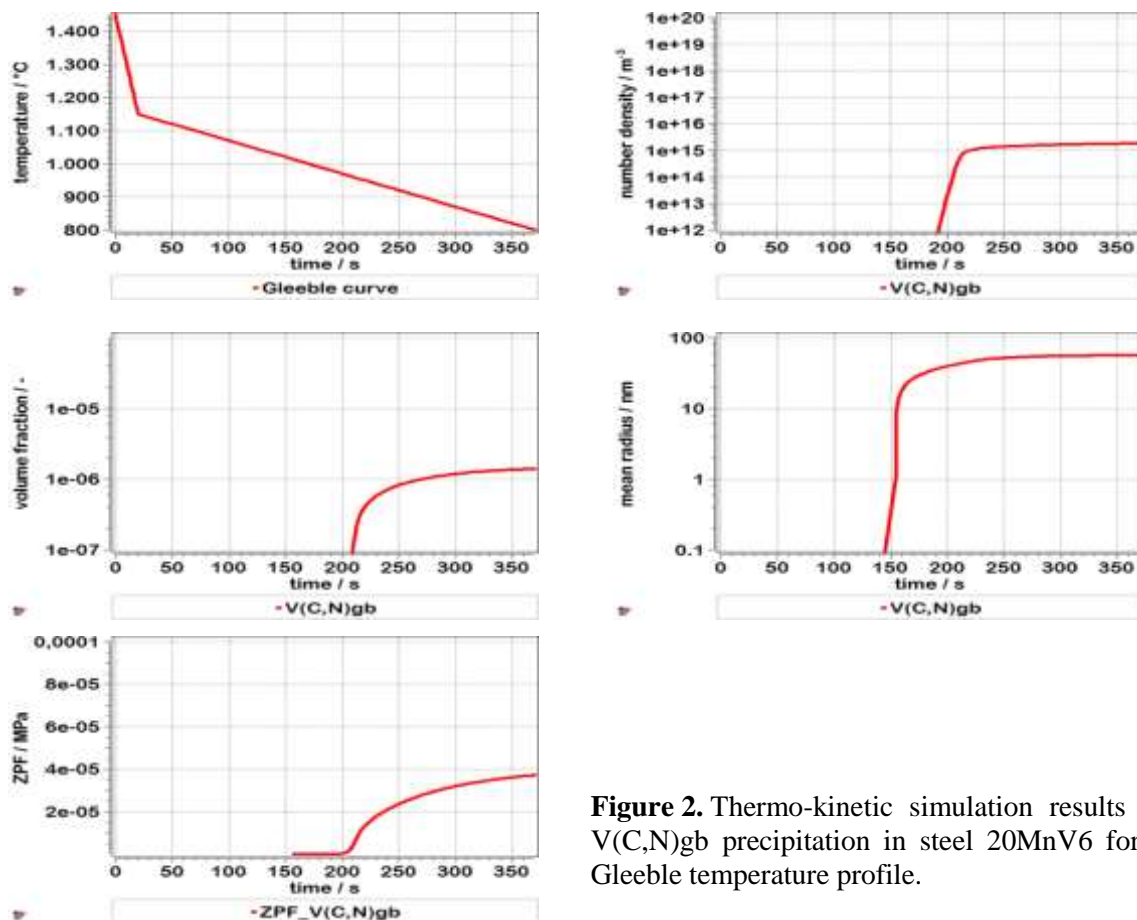


Figure 2. Thermo-kinetic simulation results of V(C,N)gb precipitation in steel 20MnV6 for a Gleeble temperature profile.

Figure 3 shows the comparison of RoA values for three steel grades related to figure 1. Mintz [3] evaluated a critical value of 40 % RoA from his experimental data (valid for a certain strain rate), which is necessary to prevent transverse surface cracking during continuous casting, which is drawn as dashed line in the comparison diagram. It should be noted that the measured temperature-dependent hot ductility of the steels shows mainly the general trend of the loss in ductility influenced by combined effects of such as MnS, V(C,N) and (AlN) formation. Lowest RoA values indicate a high cracking sensitivity and poor ductility of the steel. Since the steels 20MnV6 and 27MnSiVS6 show a similar hot ductility loss in the temperature range of unbending operations during continuous casting, it cannot be estimated which of the steels 20MnV6 and 27MnSiVS6 has a higher cracking risk. According to the casting practice it is known that 20MnV6 exhibits higher crack intensity.

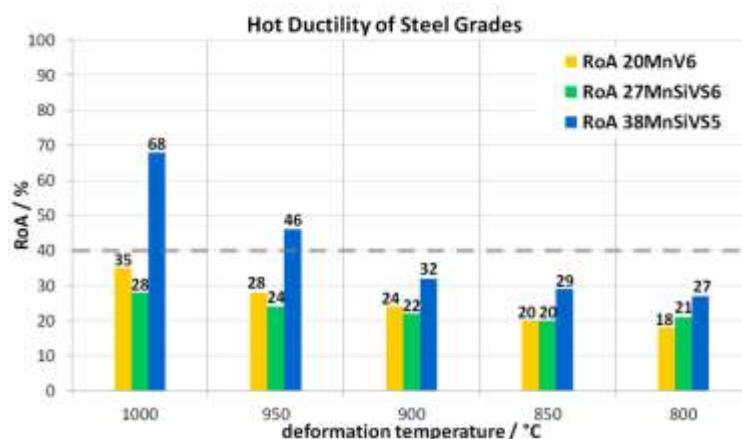


Figure 3. Gleeble experiments: Temperature-dependent hot ductility values for the examined steel grades related to figure 1.

Zener pinning force simulation results for V(C,N)gb precipitation obtained for the Gleeble temperature profiles can be seen in figure 4. The results show that values of the ZPF for V(C,N)gb correlate with the RoA values: Higher ZPF values have an adverse effect on the ductility of the material, meaning that reduction of area values decrease as the ZPF increases. Figure 4 shows that 20MnV6 is most crack sensitive.

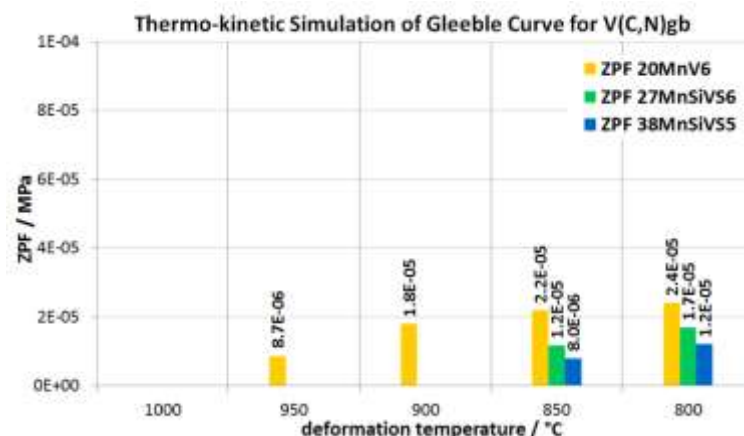


Figure 4. Gleeble experiments: Simulation results of the Zener pinning force for V(C,N)gb precipitation in the examined steel grades.

4.2. Thermo-kinetic simulation of continuously cast bloom edge temperature profiles

Figure 5 presents the results of kinetic simulations of V(C,N)gb precipitation based on the two simplified surface edge temperature profiles. According to the experience of the casting practice at ArcelorMittal Duisburg the best results have been achieved for the prevention of edge cracks with a soft cooling strategy in steel grade 20MnV6. The surface target temperature for the edges is increased by 70 K during unbending (at a time of 1300 sec.). With this cooling strategy a significant increase in the ductility as a consequence of reduced V(C,N) precipitation can be observed. According to the simulation results the precipitation of V(C,N)gb starts earlier applying a hard cooling than soft cooling. When comparing two cooling patterns, it can be seen that soft cooling profile induces lower Zener pinning forces at the entry of unbending zone and reaches to a similar level of hard cooling at the end of unbending. The kinetic simulations carried out confirm that by applying a soft cooling for steel 20MnV6 the surface edge cracking risk can be minimised.

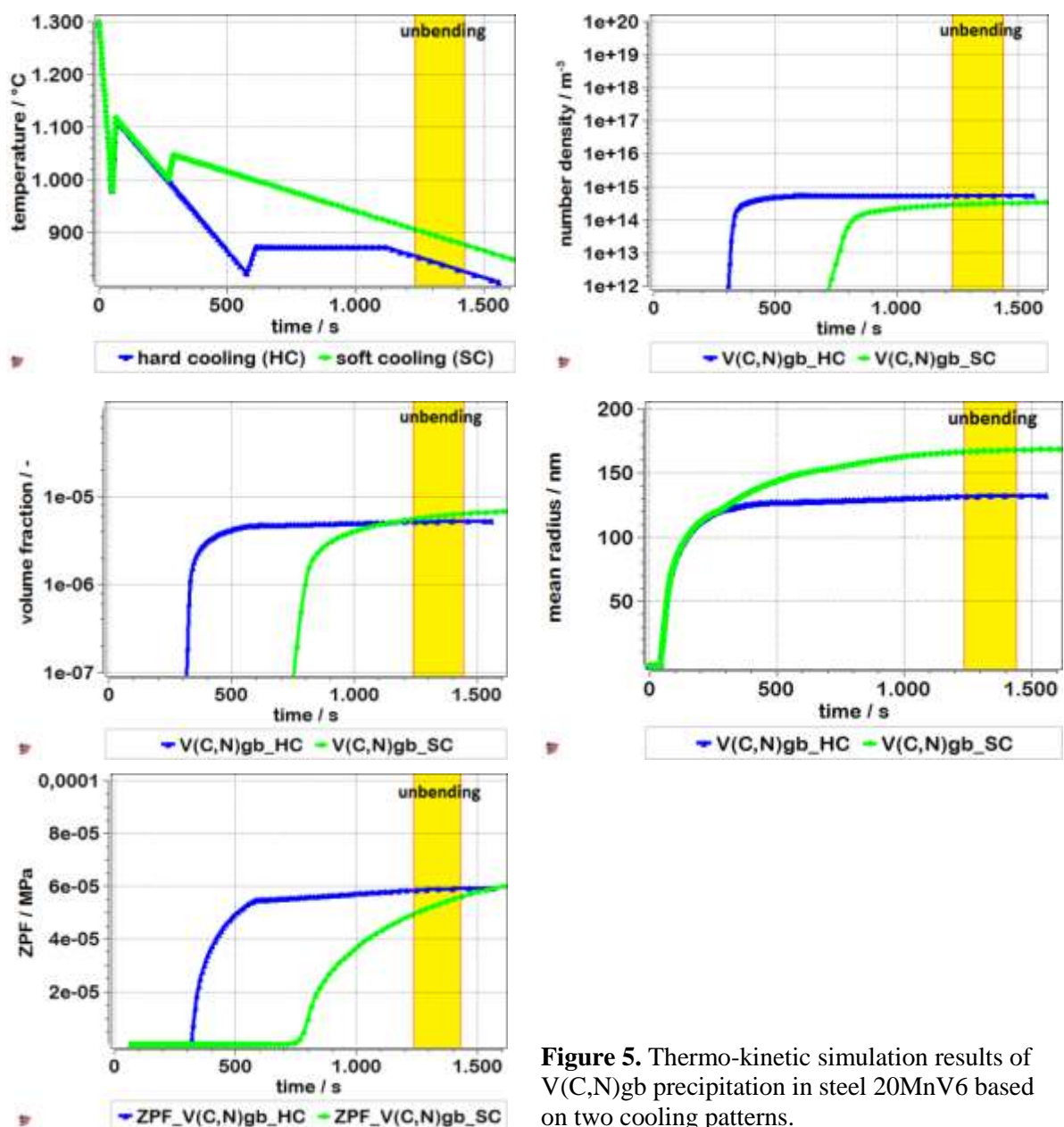


Figure 5. Thermo-kinetic simulation results of V(C,N)gb precipitation in steel 20MnV6 based on two cooling patterns.

5. Conclusion

In this paper, a new approach is introduced to characterise the transverse surface edge cracking susceptibility below the upper temperature limit of the second ductility trough which is caused by precipitates by means of thermo-kinetic modelling. It is not sufficient to assess the precipitate radius and volume fraction separately to estimate the crack sensitivity of the steel. The new approach combines the pinning effect of second phase particles on grain boundaries during continuous casting of blooms with ductility values resulting from tensile tests directly after melting and re-solidifying of the samples using a Gleeble machine. The Zener pinning force (ZPF) effect is particularly important when the volume fraction of precipitates becomes large and the mean size becomes small by generating ductility loss in the critical temperature range where the strand unbending takes place.

From the simulations it is shown that an increase in Zener pinning forces resulting from V(C,N) particles on grain boundaries can be used as an indicator for ductility in the studied vanadium containing micro-alloyed steel grades. Using the values of ZPF, it is possible to predict the edge cracking risk on the surface of the blooms for different process parameters of continuously cast blooms. On the basis of thermo-kinetic calculations, improved process parameters can lead to significant reduction in crack formation and thus to an increase in casting throughput.

Further simulations for precipitation under casting conditions are planned to be conducted to study the effect of Zener pinning force on the crack sensitivity of vanadium micro-alloyed grades 38MnSiVS5 and 27MnSiVS6.

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