Galling in 316 Stainless Steel

Samuel Rogers[1], David Dye[1], David Bowden[2], Fabio Scellini[2], David Stewart[3]

[1]Imperial College London, [2]Manchester University, [3]Rolls-Royce plc.

Introduction

Galling is an adhesive wear mechanism which is active at slow sliding speeds, relatively high compressive stresses and is known to cause the gross plastic deformation of mated surfaces [1], particularly when their movement is bound e.g. in valves [2]. Cobalt-based alloys have been developed previously that show galling resistance. However, due to increased safety measures in the nuclear industry, cobalt use is to be removed from PWR (pressurised water reactor) systems and thus an alternative and cobalt-free alloy needs to be developed [3]. Before alloy development can occur, the nature of galling and the interplay between microstructure and galling are to be investigated. Of particular interest in this work is the presence and effect of oxides on the galling behaviour of 316 stainless steel, a material which has previously provided a base for Co-free hardfacing alloy design.

Oxide Characterisation

XRD analysis of the oxide layer (Figure 1) formed during autoclaving shows the presence of austenite and magnetite (M_3O_4). As seen in Figure 1(b) and (c) doublets are seen only for the magnetite peaks, which is indicative of multiple oxides with the same crystal structure but different lattice parameters and therefore compositions.

STEM imaging and STEM-EDX were therefore performed on the oxides (Figure 2), showing the presence of multiple oxides with differing composition. The outer oxide is seen to be an Fe-rich magnetite of approximate composition Fe_3O_4. The inner oxide is seen to be a Cr-rich and Fe-rich magnetite with the approximate composition $Fe_{1.2}Cr_{1.3}Ni_{0.5}O_4$.

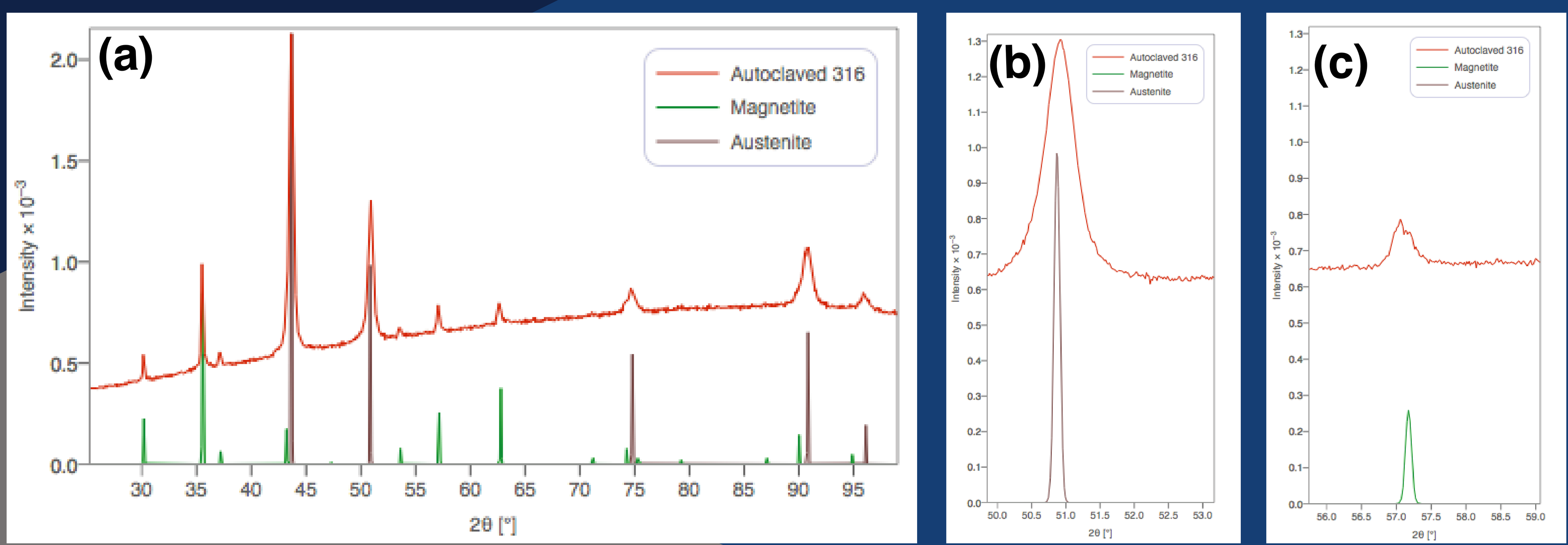

Figure 1: (a) The XRD spectrum of a sample of 316 stainless steel which had been immersed in simulated PWR water conditions for 850 hours, showing the presence of (b) austenite and (c) multiple oxides with a M_3O_4 crystal structure (e.g. magnetite).

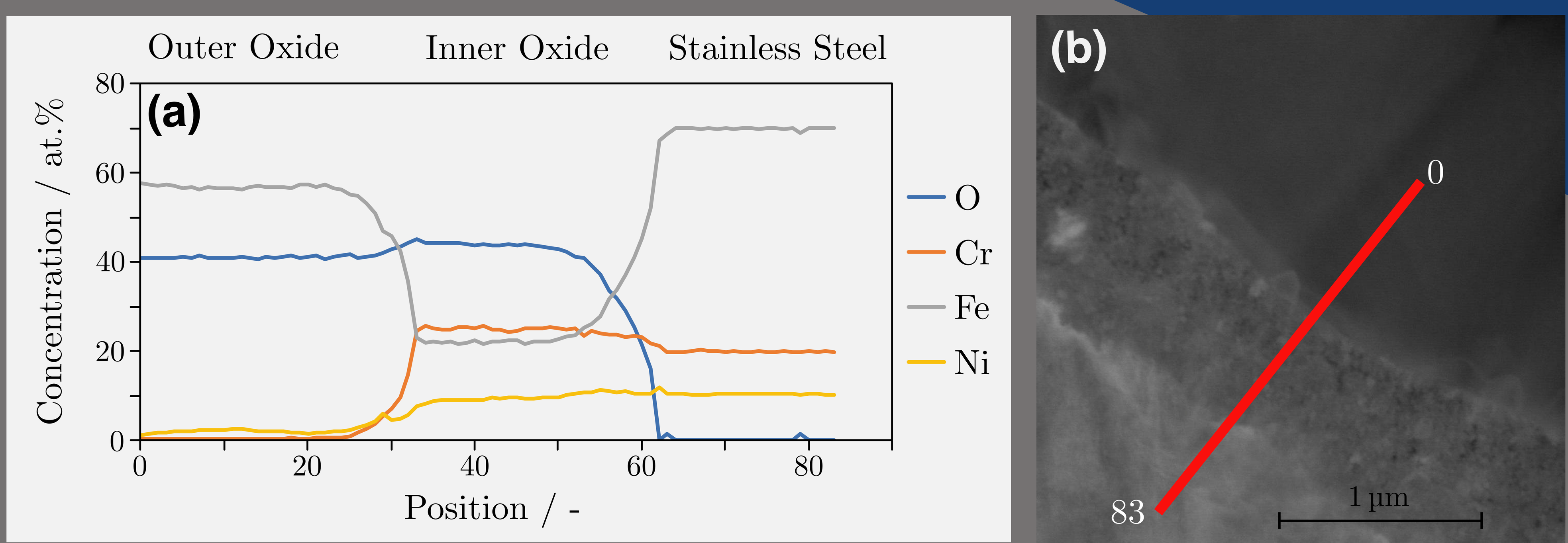

Figure 2: (a) The concentration profiles produced using STEM-EDX for the four primary elements in the oxides produced through autoclaving of 316 stainless steel. (b) A STEM image showing a cross-section of the oxides and the position of the STEM-EDX line scan.

Methods

Galling samples were oxidised for 850 hours in simulated PWR water conditions: 300 °C; 120 bar pressure; 2 ppm Li as LiOH; 10.5 pH.

Galling was acheived using a specially designed galling rig at Manchester University, supplied by Rolls-Royce. Torque is applied in small amounts using a torque wrench, whilst a compressive load is applied using a hydraulic loading cylinder. The sliding speed was approximately 1 rpm. Compressive stresses of 5 - 103 MPa were used to vary galling behaviour.

Galling parameters were calculated using a Veeco white light interferometer (WLI) in conjunction with code written to interpolate the data, apply tilt corrections, and finally measure the sample damage. Examples of the sample surfaces collected by WLI and corrected are seen in Figure 3(e - f).

Oxide characterisation was performed using XRD, TEM and STEM-EDX and galling behaviour was investigated using SEM.

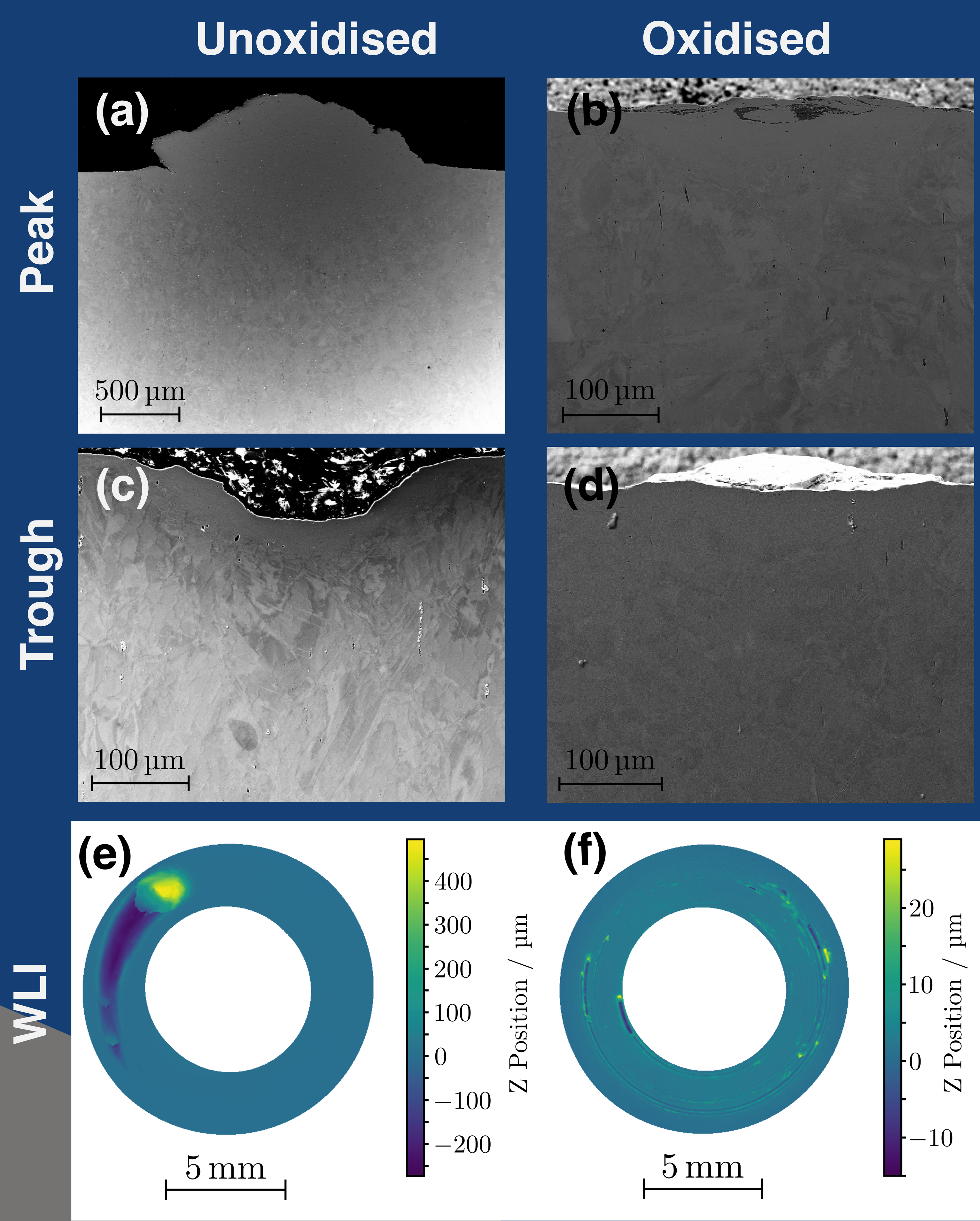

Figure 3: (a -d) SEM images of galling damage in an unoxidised sample tested at 5 MPa (a, c) and an oxidised sample tested at 25 MPa (b, d). Corrected WLI images of unoxidised and oxidised samples tested at 5 MPa (e, f).

Galling Behaviour

The galling behaviour of 316 stainless steel s found to vary considerably with the presence of an oxide layer, Figures 3 & 4. What is most prominant to see is the change in height of the peaks, even though the oxidised sample shown in Figure 3(b) was galled at a higher load than that of the unoxidised sample shown in Figure 3(a). In addition, the oxidised peak shows clear mechanical mixing of the oxide layer with the underlying metal. It is currently unconfirmed whether mechanical mixing also occurs within the unoxidised peak, since the microstructure is not clearly visible, instead showing features indicative of high shear.

Within the peaks and immediately beneath the trough of the gall scars the microstructure is seen to vary from the bulk microstructure. This is most clearly visible in Figure 3(c). This layer appears to be heavily sheared, to the extent that the prior microstructure is no longer discernable. This layer has been termed the 'tribologically affected zone' (TAZ) and is thought to be formed through the adhesion and shear of the interfacial region. The microstructure and features of the TAZ are yet to be identified.

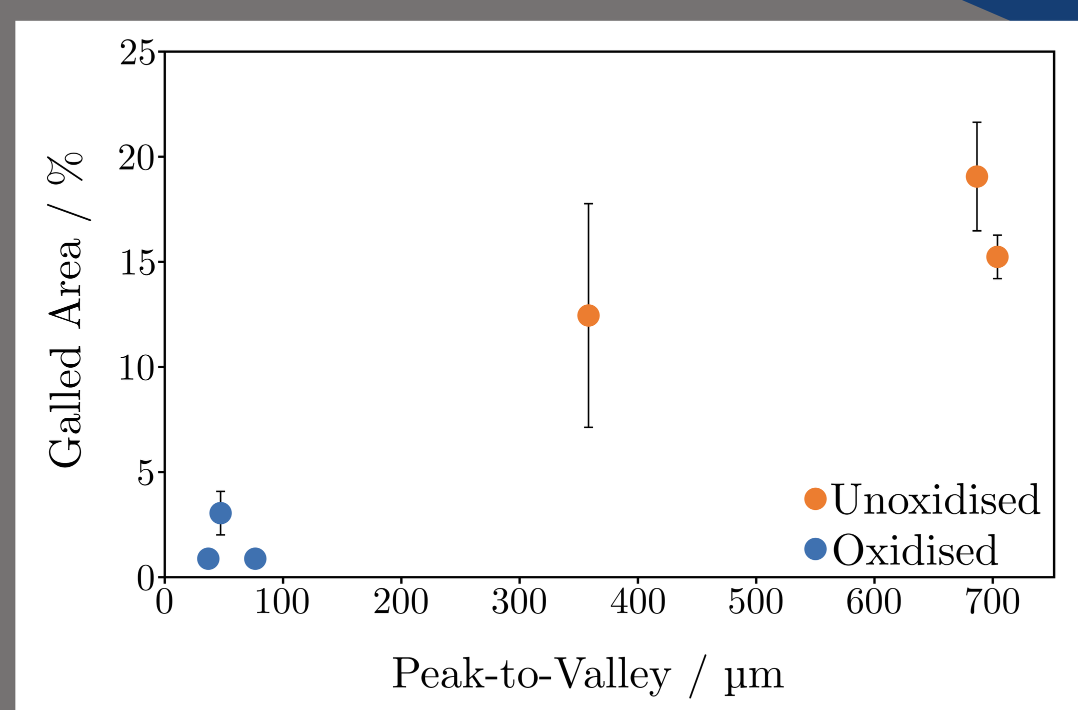

Figure 4: Galling severity for unoxidised and oxidised 316 stainless steel using galling severity measures of peak-to-valley size and galled area. All samples were tested using an applied compressive stress of 5 MPa.

Conclusions & Further Work

The oxide layers on 316 stainless steel after autoclaving in simulated PWR water conditions for 850 hours have been characterised and found to be Fe-rich and Cr-rich magnetite layers, respectively. The presence of these oxides has been found to significantly improve the galling resistance of 316 stainless steel, particularly when using the measures of peak-to-valley size and galled area. The presence of a tribologically affected zone has been identified within galling peaks and immediately below galling troughs but is yet to be fully characterised.

References

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