Emmanouil Stavroulakis (UoM), Dr. David Stewart (Rolls-Royce PLC), Prof. Peter Lee (UoM), Prof. Michael Preuss (UoM)

Functionally graded components for nuclear applications

Hot Isostatic Pressing and functional grading

Powder Hot Isostatic Pressing (HIP) is a metallurgy process for consolidating powder particles (*figure 1a*). High temperature and pressure are applied simultaneously to form a component of complete theoretical density. The application of pressure allows for elimination of porosity and mitigation of grain growth. A near net shape component is produced, with better chemical homogeneity in comparison to traditional casting [1].

The aim of the project is to develop functionally graded components (*figure 1b*) through the HIP process. So far, components are in general made from a single type of material. However, the possibility of hot isostatically pressing two different types of material together would address the need of varying performance along a component.

Functional grading of two different types of steel is investigated, namely 316L austenitic and SA508 grade 3 bainitic stainless steel. An example of the resulting microstructure after HIP is provided below (*figure 1c*):

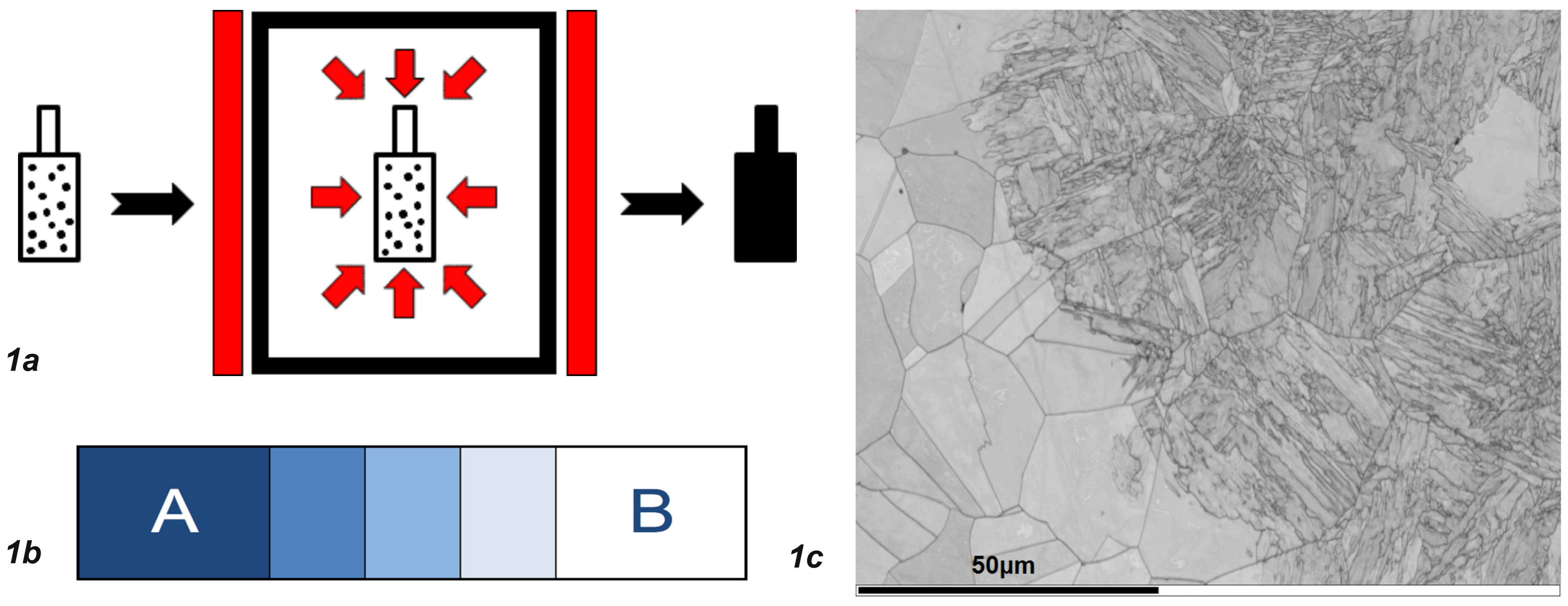

Figure 1a: Hot Isostatic Pressing (HIP) schematic. Powder is encapsulated, then high temperature and pressure are simultaneously applied to produce the final completely densified component. ***Figure 1b:*** Visual representation of a functionally graded component. ***Figure 1c:*** Band contrast map recorded by EBSD, dark phase consisting of laths is ferrite and light phase is austenite

Nuclear Industry Application

HIP of functionally graded powders could be used to join components of different materials in nuclear industry. If such functionally graded components can provide the desired microstructure and properties at the adjoining positions, they could lead to fewer dissimilar metal welds required. Dissimilar metal welds represent weak spots due to induced strains and stresses, related to the bonding of dissimilar metals and their different thermal expansion coefficients [2]. Enhanced properties at the adjoining positions would lead to a longer component lifecycle. At the same time less dissimilar metal welds decrease the need for inspection during operation, thus reducing cost.

Experimental Approach

In order to simulate a functionally graded component, different ratios of 316L and SA508 grade 2 powders were mixed and subsequently hot isostatically pressed. The ratios vary from 100% 316L to 100% SA508. Additionally, specimens of full theoretical density were acquired after a complete HIP cycle, as well as specimens of partial HIP cycles without any dwelling time and at various temperatures, in order to study the evolution of microstructure during the different stages of HIP processing.

Results and Future Work

The Electron Backscatter Diffraction - EBSD maps (*figure 2*) of a partial HIP cycle at two different temperatures reveal a change in the microstructure related to the HIP temperature. At low temperature, i.e. 950^{o}C, there are large equiaxed ferrite grains that change to a fine lath microstructure on the interface with austenite grains. At high temperature, i.e. 1120^{o}C, the fine ferritic microstructure prevails. The fine microstructure on the interface could be affected by element diffusion. *Figure 3* depicts such a fine microstructure zone, as well as a qualitative assessment of Cr and Ni diffusion from 316L towards the low-alloyed SA508, for the low and high partial HIP cycle temperature, i.e. 950^{o}C and 1120^{o}C respectively. It can be noted that enhanced diffusion of Cr and Ni takes place along the grain boundaries. Also, diffusion is more pronounced at the higher temperature, as expected.

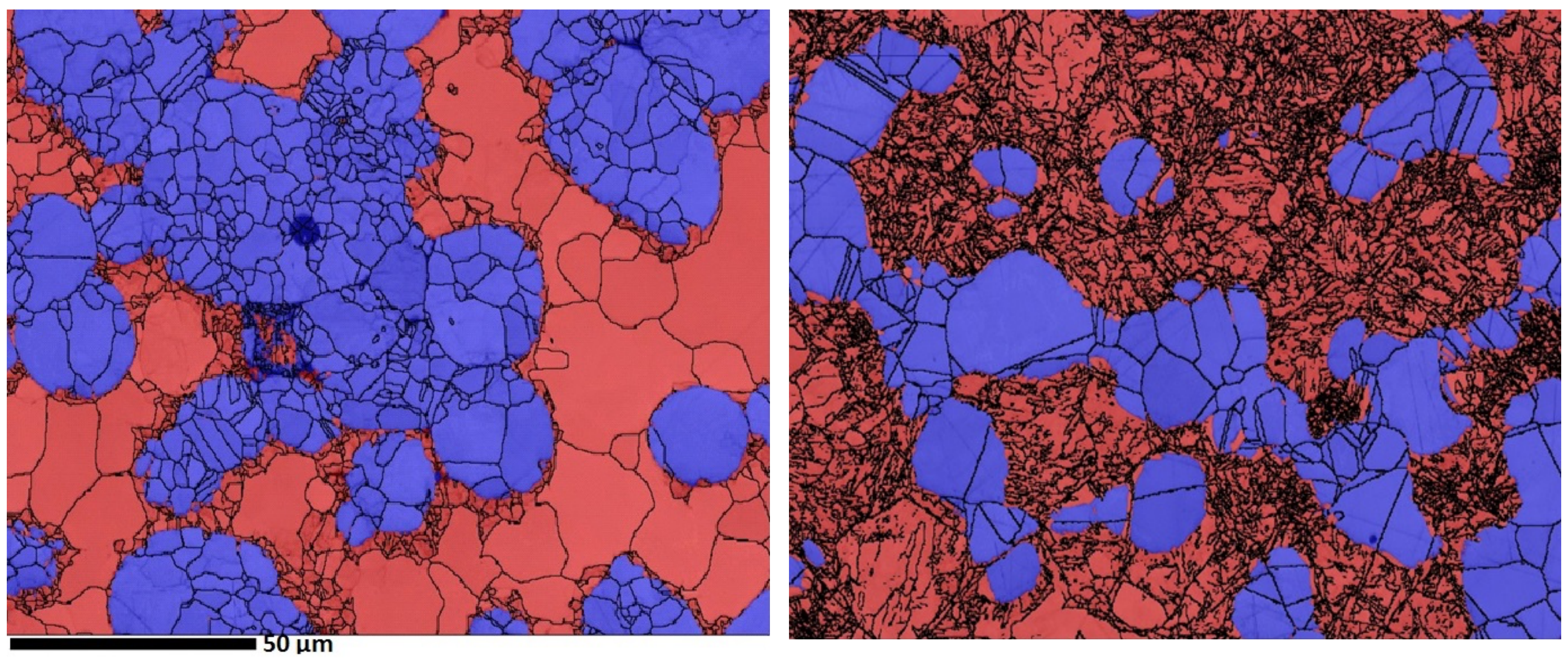

***Figure 2**:* EBSD maps, red corresponds to ferrite, blue to austenite, **left:** low temperature (950^{o}C) partial HIP cycle, **right:** high temperature (1120^{o}C) partial HIP cycle

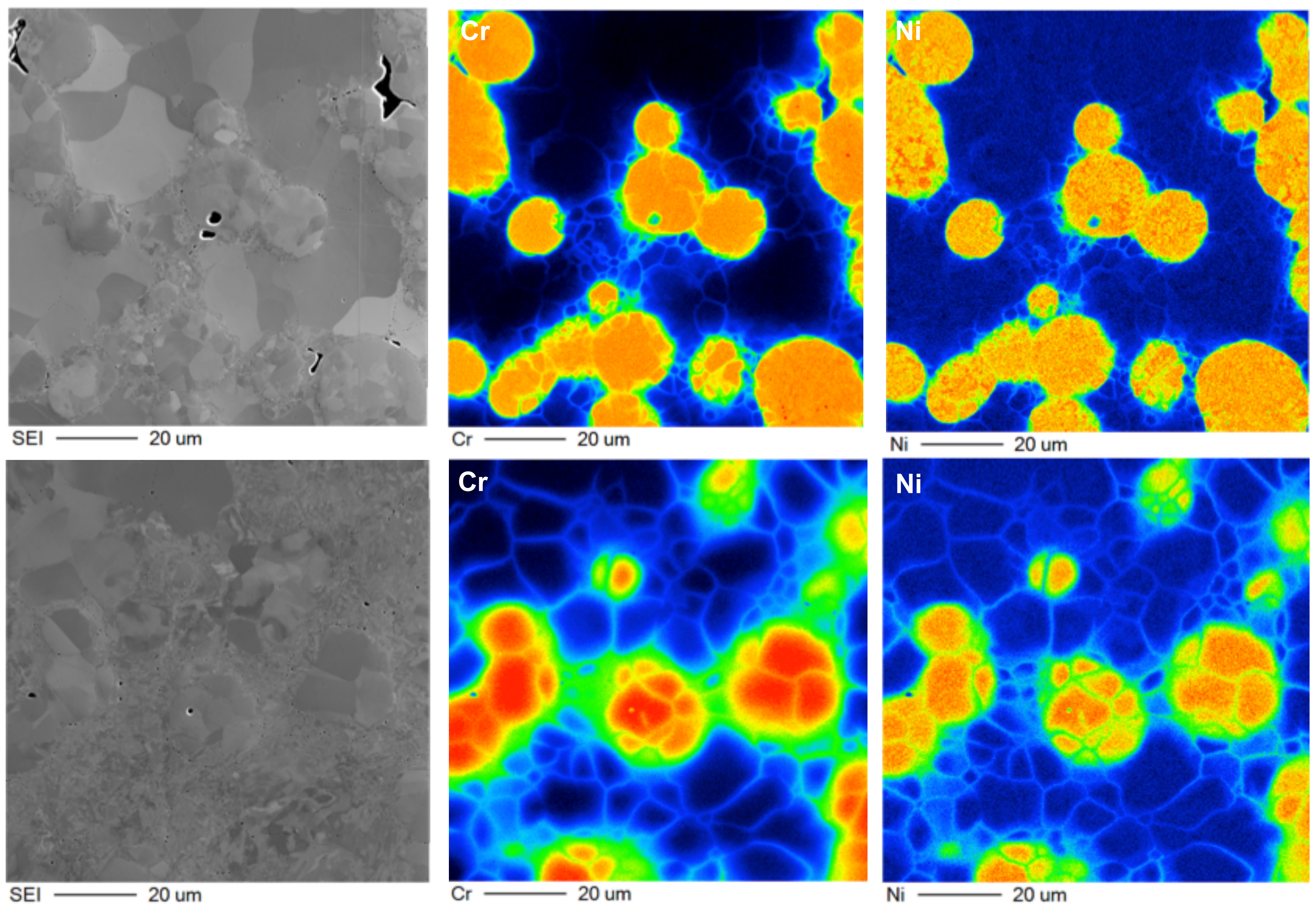

Figure 3**:* Qualitative electron microprobe analysis (EPMA), Wavelength dispersive spectroscopy, Secondary electron image of interdiffusion zones and diffusion of Cr and Ni. Red areas in the element maps correspond to the rich in Cr and Ni austenitic 316L, whereas blue areas to the poor in Cr and Ni ferritic SA508. ***First row: Partial (no dwelling time) HIP cycle at 950^{o}C, ***Second row:*** Partial (no dwelling time) HIP cycle at 1120^{o}C

- Future work will address the mechanisms that affect the development of the microstructure during the HIP process, e.g. diffusion of elements and recrystallisation processes.
- Mechanical testing will be performed at various temperatures, in order to link the resulting microstructure with the corresponding mechanical properties.

References

[1] H. V. Atkinson and B. A. Rickinson, Hot Isostatic Pressing, Bristol: Adam Hilger, 1991.

[2] H. Burlet, M. Martinez and G. Cailletaud, "Microstructure and residual stresses issued from the bonding of an austenitic onto a ferritic steel by solid diffusion," *J. Phys.*, vol. IV, no. 11, pp. 157-164, 2001.