CHAPTER 9   CONCLUSIONS AND RECOMMENDATIONS

Traditional wax-based investment casting involves the following key steps:

- Making of a disposable pattern by injecting wax into a metal mould
- Building a ceramic shell mould by repeatedly dip-coating the pattern in ceramic slurries
- Dewaxing the green ceramic shell
- Firing it to prepare the final ceramic mould
- Casting the molten metal into the shell mould, and
- Removing the shell by mechanical or chemical means to leave a near-net shape metal part.

Urea is a low-cost material and its widespread availability and low toxicity make it an attractive material for investment casting moulding compounds. Indeed, urea is used for this purpose (as a wax replacement) with polyvinyl alcohol (PVOH) used as binder. However, owing to their higher viscosities, the urea-based moulding compounds are injection-moulded just like conventional plastics. Nevertheless, the conventional cooking process requires the preparation of a water-ethanol solution and the subsequent evaporation of the solvents. This study found that it is possible to prepare such urea-based moulding compounds using a conventional polymer compounding procedure. Two systems were investigated:

- With PVOH as binder, it was necessary to plasticise the polymer. It was found that glycerol was a suitable plasticiser which lowered the processing temperature sufficiently to allow the incorporation of urea without it degrading.
- A low-melting EVA also provided a suitable binder for the urea but continuously processable formulations had lower urea contents.

The conventional cooked urea-based compound was used as benchmark composition. This study investigated the effect of the composition on the properties of the two types of compound investigated. Two-way ANOVA was used as a statistical tool to determine which variable had a significant effect. The properties of the two preferred compositions developed and tested in this study are presented in Table 34.

Samples were compounded on a two-roll mill and also on a co-rotating twin-screw compounder. It was possible to injection mould PVOH urea-based moulding compounds with a urea content of up to 90% which had been compounded using a two-roll mill. Using the conventional extrusion process, it was also possible to compound and injection mould EVA urea-based moulding compounds containing up to 70% urea content.

The thermal properties of the compounds are relevant to the pattern's injection-moulding step. Urea degrades just above its melting point of 132°C and this sets an upper limit to the processing temperature. Important factors are the lowest temperature at which the material becomes flowable, and thus mouldable, and the rate of crystallisation. The latter affects the injection-moulding cycle time. The sub-cooling required before crystallisation sets in provides an indication of the material's propensity to crystallise rapidly.

The EVA urea-based moulding compounds showed two endothermic melting peaks and multiple exothermic crystallisation peaks in the DSC curves. The peak at ca. 55 -66°C corresponds to the melting of the wax/EVA blend, while the large peak at 130-132°C corresponds to the melting of the urea. The DSC heating curve of the PVOH urea-based moulding compounds showed two endothermic peaks. The small peak corresponds to the melting of the wax, while the large peak corresponds to the melting of the urea/PVOH blend. The cooked urea-based moulding compound showed one endothermic peak and it had the lowest melting point. Both the wax and polymer contents affected the rate of crystallisation, as evidenced by the high on-set temperature in the DSC cooling curves. However, the composition dependence was found to be highly non-linear.

The moulded patterns should have reasonable mechanical properties, allowing them to survive the wear and tear of the ordinary handling commonly encountered in a manufacturing plant. This study used three-point bending as the primary indicator of mechanical properties, i.e. strength (flexural stress), stiffness (flexural modulus) and deformation limit (flexural strain). In addition, unnotched Charpy impact strength was used as a measure of toughness. Table 32 shows that the PVOH urea-based moulding compound had better mechanical properties than the industrial benchmark. The mechanical properties of the EVA urea-based compound were

generally lower. This is not surprising as the EVA was of a grade with a low molecular mass and it was not expected to interact as strongly with urea (due to hydrogen bonding) as the PVOH.

The effect of the wax and polymer content on the mechanical properties was as follows:
- Increasing polymer content produced weaker but tougher moulding compounds.
- Increasing wax content improved the strength and stiffness but gave compounds that were less tough.
- Two-way ANOVA indicated significant polymer-wax interactions.

The urea content determined the stiffness (elastic modulus) of the compounds. PVOH mouldings had superior stiffness compared with the EVA and cooked urea-based mouldings. The DMA results confirmed the result obtained from the modulus of elasticity in the three-point bending test.

The unnotched Charpy impact test was used to quantify the impact strength in order to determine the toughness of the moulding compounds. The impact strength increased with an increase in polymer content and reduced with an increase in wax content.

The coated patterns are heated to "de-wax" the green shells. In this process step it is necessary that the thermal expansion of the pattern material should be sufficiently low for the green shells not to crack. The linear thermal expansion coefficient generally decreased as the urea content was increased. The measured values were comparable to those of the benchmark and ranged from 100 to 156 x 10^{-6} °C.

Viscosity is an important parameter in the "de-waxing" process of the green shells. Once molten, the moulding compound should have a low viscosity (high fluidity) to allow it to flow out of the shells easily. The melt flow index (MFI) of a compound is proportional to the inverse of the viscosity and thus provides a measure of the fluidity. The MFI measured at 110°C was taken as a measure of the fluidity of the compound. The benchmark MFI was higher than that of the two compounds proposed as alternatives. The cooked urea-based moulding compound had the lowest viscosity at 110°C, as indicated by its MFI. This suggests that it would be more difficult to remove the PVOH and EVA moulding compounds from the ceramic shell.

Table 34:   Properties of the cooked urea moulding compound (benchmark) compared with those of the best PVOH and EVA moulding compounds

Property	Units	Cooked urea (benchmark)	UP4 90:5:5	UE 70:20:10
Mechanical properties				
Three-point bending test				
Flexural stress	MPa	37,0	47,7	9,15
Flexural strain	%	0,92	0,74	0,81
Modulus of elasticity	GPa	8,5	11,4	3,43
Fracture energy	J	67,7	71,44	14,4
Charpy impact strength	kJ/m^2	0,56	0,84	1,95
Thermal properties				
Ash content (residue at 800 °C)	Mass, %	1,31	0,37	0,0
Temperature to 97% mass loss	°C	472	498	365
Flow properties				
MFI	dg/min@ 110°C	44,5	6,45	24,4
Thermo-mechanical properties				
Linear thermal expansion coefficient	10^{-6}°C	121	100	156
Vicat softening temperature	°C	57,2	74,5	76,5
Dynamic mechanical properties				
Storage modulus @ 25 °C	10^8 Pa	5,66	6,85	4,89

Once most of the moulding compound has been removed from the shells, the rest should decompose to leave very little residue. This property was characterised by the ash content as measured from the residue remaining at 800°C in the thermogravimetric analysis (TGA). The TGA results confirmed that both the PVOH and EVA urea-based moulding compounds decomposed readily and left less than 1% ash.

Good-quality metal parts should have an acceptable surface finish. This implies that the patterns should have an acceptable surface texture. Scanning electron microscopy (SEM) was used to get

a qualitative idea of the surface and it was found that injection-moulded samples of the cooked and PVOH urea-based moulding compounds gave similar surface finishes. The apparent surface roughness appeared to increase with wax content. The EVA urea-based moulding compound had an irregular surface texture. This could be because of weak interaction of hydrophobic EVA with hydrophilic urea.

Polyvinyl alcohol is fully biodegradable. It also tolerates higher urea contents than the EVA binder. Use of the PVOH urea-based moulding compound is therefore preferable based on its cost-effectiveness and environmental friendliness. However, conventional extrusion-compounding processes can be used to manufacture of the EVA-urea compound. This process has the added advantage that the need for the energy-intensive evaporation of the solvents necessary in the conventional cooking process can be avoided.