

List of Figures

Figure 1.1- E-waste generation of world and India (in million tons) [26]	9
Figure 1.2- General flow sheet of illegal WEEE recycling [34,35,48]	10
Figure 1.3- Schematic view of cross-section of PCBs	14
Figure 1.4- Unit processes in conventional recycling of WPCBs.....	17
Figure 1.5- Various techniques exercised for the mechanical processing of WPCBs	21
Figure 1.6- Overall flow sheet of pyrometallurgical processes investigated for WPCBs recycling.....	28
Figure 1.7- Steps of hydrometallurgical processing of e-waste.....	33
Figure 1.8- Flow sheet of hydrometallurgical recycling of WPCBs.....	38
Figure 2.1- Flow-sheet showing the mechanical pre-processing of WPCBs.....	52
Figure 2.2- Schematic view of the experimental setup used for digestion	53
Figure 2.3- Thermal degradation profile of WPCBs in different atmosphere	56
Figure 2.4- Hammer Mill and its milling chamber	57
Figure 2.6- Schematic view of experimental Setup for dissolution of HER.....	61
Figure 2.7 – Chemical structure of (A) polymer chain of halogenated epoxy resin; (B) BisPhenol-A.....	62
Figure 2.8 - Absorption curve for varying concentration of BPA	62
Figure 2.9- Schematic diagram of hydrothermal autoclave bomb used for leaching of copper.....	67
Figure 2.10- Solder material collected during the pre-processing	68
Figure 3.1- Distribution of WPCBs in –1 mm and +1 mm size at different milling time	74
Figure 3.2- Amount of WPCBs milled to -1 mm at different feed rate	75
Figure 3.3- Particle size distribution of WPCBs powder (-1 mm).....	76
Figure 3.4- Distribution of crushed WPCBs in various size fractions at different milling time	76
Figure 3.5- Distribution of copper in various size fractions of milled WPCBs after different milling time	77
Figure 3.6- Copper, glass fibre and non-metallic particles in microscopic image of crushed WPCB (- 1 mm) after 7 minute	78
Figure 3.7- SEM image of ground WPCBs after 7 min milling	79
Figure 3.8- The graphical representation of the milling operation	81
Figure 3.9- Effect of temperature on dissolution of HER.....	86

Figure 3.10- Improved delamination of WPCBs with rise in reaction temperature	87
Figure 3.11- Effect of WPCB:DMF ratio on dissolution of HER	88
Figure 3.12- Effect of PCB size on dissolution of HER.....	89
Figure 3.13- Representation of interaction of DMF on cross-section of WPCB	90
Figure 3.14- Effect of time on dissolution of HER in DMF.....	91
Figure 3.15- Separated components of WPCB (a) glass fibre (b) solder mask (c) copper laminates.....	92
Figure 3.16- (A) Unused DMF, (B) pregnant DMF, and (C) Regenerated liquid.....	92
Figure 3.17- (A) ¹ H-NMR (B) ¹³ C-NMR spectra of unused and regenerated DMF	94
Figure 3.18- FT-IR spectra of unused and regenerated DMF	94
Figure 3.19- Dissolution of HER in fresh DMF and five times regenerated DMF [WPCB:DMF- 3:10, 4 h, 135 °C, WPCB size- 1 cm ²].....	95
Figure 3.20- Morphology and elemental composition of (A) residue and (B) untreated HER	96
Figure 3.21- FT-IR spectra of pure BPA, residue, and untreated BPA	97
Figure 3.22- Chemical structure of DMF and its hydrogen bonding moieties.....	99
Figure 3.23- Hydrogen bond interactions resulting dissolution of HER into DMF	99
Figure 3.24- Flow sheet of the proposed process for dissolution of HER by using DMF	100
Figure 3.25- Effect of temperature on dissolution of HER at different time.....	106
Figure 3.26- Digital photographs of WPCBs at different time.....	107
Figure 3.27- Effect of WPCB:DMA (wt/vol) ratio on dissolution of HER at different time.....	107
Figure 3.28- Dissolution of solder mask after different time [WPCB:DMA- 3:10, 160 °C, WPCB size- 1 cm ²].....	108
Figure 3.29- Effect of fed WPCB size on dissolution of HER.....	109
Figure 3.30- Schematic view of through holes that hinders the easy liberation of WPCBs layers.....	110
Figure 3.31- Components of DMA treated WPCBs (A) copped laminates and (B) glass fibre matrix	110
Figure 3.32- Physical appearance of pure DMA, used DMA and regenerated liquid.....	111
Figure 3.33- ¹ H-NMR spectra of pure DMA and regenerated liquid.....	112
Figure 3.34- ¹³ C-NMR spectra of pure DMA and regenerated liquid.....	112
Figure 3.35- FT-IR spectrum of pure and recycled DMA.....	113

Figure 3.36- TGA-DTG analysis data of (A) pure DMA and (B) regenerated liquid	114
Figure 3.37- GC spectrum of pure DMA and regenerated liquid	115
Figure 3.38- Effectiveness of DMA to dissolve HER after 15 regeneration cycle.....	116
Figure 3.39- SEM-EDX analysis of untreated HER and residue.....	117
Figure 3.40- FT-IR spectra of untreated HERS and residue.....	118
Figure 3.41- TGA-DTG analysis of (A) untreated resin and (B) recovered residue	119
Figure 3.42- Molecular structure of DMA and its major hydrogen bond acceptor moiety	120
Figure 3.43- Chemical interaction between the substrate resin and DMA resulting dissolution.....	120
Figure 3.44- Flow sheet of the proposed process for delamination of WPCB using DMA	121
Figure 3.45- Effect of temperature on the dissolution of HER.....	127
Figure 3.46- Effect of WPCB:solvent on the dissolution of HER.....	129
Figure 3.47- Effect of WPCBs size on dissolution of HER.....	130
Figure 3.48- ¹ H-NMR of DMA containing HER after 8 h	132
Figure 3.49- ¹³ C-NMR of DMA containing HER after 8 h	133
Figure 3.50- ¹ H-NMR spectra of pregnant DMA after different time interval.....	135
Figure 3.51- FT-IR of HER dissolved in DMA after varying DMA-PCB contact time.....	136
Figure 3.52- Chemical reaction taking place during DMA-PCB interaction.....	137
Figure 3.53- (A) Effect of temperature on HER dissolution, (B) Treated PCBs after 3 h, (C) Cross-section of treated PCBs [WPCB:DMA- 3:10, 4 h, WPCB size- 4 cm ²]	142
Figure 3.54- (A) Effect of temperature on HER dissolution, (B) Treated WPCBs after 5 h, (C) Cross-section of treated PCBs [WPCB:DMA- 3:10, 4 h, WPCB size- 9 cm ²]	143
Figure 3.55- (A) Effect of temperature on HER dissolution, (B) Treated PCBs after 7 h, (C) Cross-section of treated PCBs [WPCB:DMA- 3:10, 4 h]	144
Figure 3.56- Leaching of Cu from copper laminate of DMA treated WPCBs under varying concentration of oxidant hydrogen peroxide	146
Figure 3.57- Leaching of Cu from copper laminate of DMA treated WPCBs under varying concentration of oxidant nitric acid	146

Figure 3.58- Leaching of Cu from WPCBs concentrate obtained by hammer milling and sieving under varying concentration of oxidant nitric acid and hydrogen peroxide.....	147
Figure 3.59- XRD analysis of (A) DMA treated WPCBs, (B) hammer milled WPCB's concentrate, (C) residues after leaching of DMA treated WPCBs, (D) Residues after leaching of Hammer mill treated WPCBs	149
Figure 3.60- The SEM-EDS analysis of DMA treated WPCBs after crushing.....	150
Figure 3.61- EDS mapping of copper on the selected area of SEM micrograph	151
Figure 3.62- Adhered non-metallic particles on the surface of copper particles showing the charging effect	151
Figure 3.63- The SEM-EDS analysis of WPCB concentrate obtained after hammer milling and sieving	152
Figure 3.64- SEM-EDS analysis of residue after copper leaching from DMA treated WPCBs	153
Figure A.0.1- Peak indexing of protons in the HER chain.....	179
Figure A. 0.2- Peak indexing of carbon atom in the HER chain.....	181