Chapter 1
Resource Recovery and Recycling from Waste Metal Dust (I): Waste Iron Dust and Waste Aluminum Dust

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1.1 Waste Metal Dusts

Extractive metallurgy uses smelting to create a metal from its ore [1]. Heat and a chemical reduction agent are used in smelting to break down the ore, removing other components as gases or slag and only leaving the metal behind [2, 3] while purifying an impure metal is the purpose of refining in the field of metallurgy [4–6]. In contrast to smelting, which results in a chemical change to the raw material, refining typically results in a purer finished product that is typically chemically same to the original [7].

However, in order to convert metal ores like copper glance [8, 9], pisolitic ironstone [10], bauxite [11], and galena [12] into pure copper, iron, aluminum, and lead, respectively, these two metallurgical processes need to reach extremely high temperatures. As a result, throughout the smelting process, it is crucial to know these metals' melting points, for instance, copper melts at 1085 °C [13, 14], iron melts at 1536 °C [15, 16], aluminum melts at 660 °C [17], lead melts at 328 °C [18] and so on. Many other metals and metal compounds also melt or volatilize at these temperatures; for instance, lead has a melting point of 328 °C [18], and mercury, cadmium, zinc, and arsenic all have boiling points of 357 °C [19], 765 °C [20], 906 °C [21], and 613 °C [22], respectively.

Wastes are produced during the metal smelting and refining processes, including dusts among others [23]. Metals including copper, iron, aluminum, lead, zinc, nickel, cadmium, chromium, mercury, selenium, arsenic, cobalt, etc., are frequently found in these wastes.

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To create metal alloys, these elements may be present in the ores utilized or they may be introduced as mixed metals to the melting [24].

In this chapter, the dusts created during metal smelting and refining are referred to as waste metal dust (WMD) because they frequently contain considerable amounts of valuable metal oxides. Due to the high metal concentrations, WMD created in the smelting furnace is categorized as both a lucrative by-product and a dangerous pollution [25]. In order to manage this type of metallurgical waste, this has inspired various researchers in the past and even now to study further acceptable ways on resource recovery and recycling from WMD.

Because of this, this chapter provides a summary of resource recovery and recycling from WMD, concentrating on the generation of WMD, their description, their recirculation or disposal, as well as modern methods for resource recovery and recycling from WMD.

1.2 Types of Waste Metal Dusts

1.2.1 Waste Iron Dust

1.2.1.1 Generation

For the most part, low-carbon stainless steels are refined using the argon oxygen decarburization (AOD) and vacuum oxygen decarburization (VOD) procedures. During the refining process, waste iron dust (WID) [26, 27] is generated. It has a significant amount of precious metal oxides of Fe, Cr, and Ni, and its production rises together with that of stainless steel [28, 29].

Several reports have been shared on its treatment, because of these valuable metals, WID often contains [30–34]. WID is metal and slag mixes that primarily found their way into the equipment used for collecting. Additionally, some WID was released from the flue gas pipelines as a result of the ferociously violent stirring of molten steel during the operations for producing stainless steel.

1.2.1.2 Description of WID

Particle Size Distribution of WID

WID is very fine material, according to all reported analyses [30, 31, 35]. Particles with a diameter of less than 5 μm made up roughly 70–90% (by weight) of the dusts, and even more of them had a diameter of less than 1 m. In WID, there are still a few sizable solid agglomerates that make about 10–30% of the total weight and may have had a diameter of more than 150 μm.

Chemical Composition of Typical WID

According to Sofilić et al. [29], the chemical species in WID depend on the quality of the steel scrap treated, the type of steel being produced, technological and operating circumstances, and the degree of dust returned into the process.

According to this assertion, Table 1.1 illustrates the several chemical species that make up the predominant composition of these WID. Since iron ore is

Table 1.1 Chemical Species in WID from Various Processing Facilities across the World

Species	Content						
	WID 1	WID 2	WID 3	WID 4	WID 5	WID 6	WID 7
CaO	14.00	6.59	9.02	9.14	12.90	9.14	2.31
SiO_2	5.60	5.76	5.14	5.45	4.81	5.45	6.42
Al_2O_3	0.70	0.74	0.64	0.66	0.40	0.66	6.67
MgO	2.60	4.25	3.63	3.48	5.44	3.48	2.35
Cr_2O_3/CrO	$14.30^{[Cr_2O_3]}$	–	$16.30^{[Cr_2O_3]}$	$15.10^{[Cr_2O_3]}$	$14.60^{[Cr_2O_3]}$	$13.51^{[CrO]}$	$9.09^{[Cr_2O_3]}$
MnO/MnO_2	$3.30^{[MnO]}$	$5.88^{[MnO]}$	$4.41^{[MnO_2]}$	$4.67^{[MnO_2]}$	$5.08^{[MnO]}$	$4.67^{[MnO_2]}$	$2.64^{[MnO]}$
Fe_2O_3	45.20	39.56	51.30	48.00	43.40	56.00	≈ 46.28
CuO	–	–	–	–	–	–	0.43
WO_3	–	–	–	–	–	–	0.91
BiO	–	–	–	–	–	–	≈ 0.07
SnO_2	–	–	–	–	–	–	≈ 0.05
TiO_2	–	0.16	0.08	0.12	0.08	–	≈ 0.07
NiO	4.30	–	6.25	6.70	2.79	6.70	2.42
ZnO	5.80	–	0.96	0.93	4.49	0.93	7.41
Na_2O	4.20	1.01	0.60	0.53	0.60	–	
K_2O	–	0.48	0.72	1.47	0.97	–	
P_2O_3	–	0.04	0.30	0.62	0.04	–	
V_2O_5	–	–	–	–	0.09	–	0.13
PbO	–	–	0.29	0.16	0.39	0.16	0.45
CdO	–	–	0.01	0.01	–	–	≈ 0.01
MoO_3	–	–	–	–	1.35	–	
CoO		–	–	–	–	–	≈ 0.04
ZrO_2	–	–	–	–	–	–	0.02
Nb_2O_5	–	–	–	–	–	–	≈ 0.07
SO_3	–	–	–	–	0.47	–	–
F	–	–	–	–	–	–	–
Cl				–	0.86	–	–
S	–	–	–	–	–	–	0.13
LOI	–	3.67	–	–	0.21	–	–
Others	–	31.86	–	–	1.45	–	9.75

Key: WID 1 = Kim and Sohn [26] (wt%); WID 2 = Laforest and Duchesne [32] (mass fraction, %); WID 3 = Tang et al. [33] (mass fraction, %, bag house); WID 4 = Tang et al. [33] (mass fraction, %, stockpile); WID 5 = Ma and Garbers-Craig [34] (mass fraction, %); WID 6 = Peng et al. (2007) (mass fraction, %, stockpile); WID 7 = Takano [36] (wt%); LOI = loss on ignition involved, Fe_2O_3 had the highest percentage in each WID (39.56–56.00%), as one might anticipate. Then comes CaO (2.31–14.00%), ZnO (0.93–7.41%), NiO (2.42–6.70%), SiO_2 (4.81–6.42%), MnO/MnO_2 (2.64–5.88%), MgO (2.35–5.44%), and Cr_2O_3/CrO (9.09–16.30%). The variety of these WID's contents and compositions places a great emphasis on the need for categorization of these WID [29]. Information like this demonstrates even more how the WID from the various sources listed in Table 1.1 differs in terms of harmful chemical species like Cr_2O_3. This has influenced how waste management strategies have been adopted [34].

Mineralogy of WID

Some researches [26, 29, 32] looked at the phase structures of the WID. Complex oxides, which frequently take the form of phases like $ZnS_2O_4Na_2S_2O_4nH_2O$ [29] and $Fe_2(SO_4)3H_2SO_42H_2O$, are abundant in the WID and predominate there. Sulfides (FeS, Fe_9S_8, Ni_7S_6 [29], and silicate SiO_2, $2FeOSiO_2$ [29]) are also present, though. Before disposal, a suitable process path has always been designed for the recovery of the valuable metals, depending on the composition of these compounds and associations.

Morphology of WID

Several researches have investigated the micro-shape of the WID constituents [29, 32, 37]. Individual particles were typically spherical [30, 37, 38] and frequently seen in aggregate forms; angular particles were uncommon [29, 39].

1.2.1.3 Stabilization/Solidification for Recirculation or Disposal of WID

WID must first be converted into briquettes using a suitable reducing agent, such as carbon, in order to be recirculated [26, 40, 41]. But because they require more binder, such as bentonite or cement, and increase the volume of slag, impurities like CaO, SiO_2, Al_2O_3, MgO, and ZnO in the recirculated WID might reduce the furnace's efficiency and use unnecessary electricity [26, 40, 42].

Recirculation to the furnace is also not an option due to the presence of harmful heavy metals, some of which are partially soluble, such as the fatal hexavalent chromium (Cr^{6+}) [26].

Should these harmful heavy metals in WID be stabilized or consolidated for ultimate disposal to class one landfill sites, like the large but expensive Vlakfontein investment in South Africa (SA) (Fig. 1.1)? Where this WID are disposed of, potential liability issues may still exist.

Fig. 1.1 Shows the enormous Vlakfontein investment in SA, which was built to address the problem of hazardous wastes. (Source: google image)

1.2.1.4 Resource Recovery and Recycling from WID

The Recovery of Metals from WID

For both economic and environmental reasons, many regions have been processing these WID during the past 20 years in order to extract the valuable metal components, such as nickel, chromium, molybdenum, and iron.

The Use of Hydrometallurgical Techniques
Four processes make up the majority of the hydrometallurgical process: roasting, leaching, purification, and electrowinning. It is a common technique for obtaining non-ferrous metals including zinc, lead, copper, and so forth. According to several commercial methods, hydrometallurgical techniques have been employed to recover Zn from WID using alkaline leaching [43–46].

The Use of Pyrometallurgical Techniques
WID mixes from several researchers have been used in laboratory size reduction smelting studies [36]. Approximately 90% of the total iron, 95% of the chromium, and practically 100% of the nickel in the WID, according to the results, may be recovered by combining molten metals at the right temperature with additives and reductants.

The Use of Physical Separation Techniques
Smaller, more polluted particles are often removed using physical separation methods. Centrifugation, sedimentation, gravity separation, magnetic separation, and other techniques are among them. According to reports, certain commercial

processes have recovered Ni and Cr from stainless-steel wastes using magnetic separation or gravity separation techniques, but the majority of research has remained in the lab [47]. When separating minerals with radically differing densities, gravity separation is an efficient technique. The recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes is frequently accomplished using magnetic separation.

Conversion of WSD into Value-Added Product

Ordoez and Colorado [48] used WID in their research as a complementing material in the additive manufacturing (AM) of kaolinite-based clays as an example of attempts toward the conversion of WID into value-added product. The direct ink writing method was the AM technique used. Since the residues can be immobilized and the water can be less contaminated, adding WID to the clay is good for the environment. The current study demonstrates the potential for employing WID in 3D printed components as well as an admixture with clay ceramics after sintering.

1.2.2 Waste Aluminum Dust

1.2.2.1 Generation

One of the materials that can be recycled the most easily is aluminum [49, 50]. In fact, according to one estimate, 75% of the aluminum that has ever been produced is still in use [51]. This is due to the existence of industrial procedures for the conversion of primary aluminum and scrap into secondary or second fusion aluminum, which generates a number of by-products.

Even so, enormous amounts are wasted as dusts (such as waste aluminum dust), slags, etc. [52], salt slag (more than 500 kg/MT Al), aluminum slag (less than 10,000 MT/year), and furnace filter fines (more than 35 kg/MT Al [53], herein referred to as waste aluminum dust), are the waste products produced in the secondary aluminum melting step (WAD).

1.2.2.2 Description of WAD

Particle Size Distribution of WAD

The particle size of the WAD examined in the study by Nifuku et al. [54] was primarily greater than 105 μm for samples 1 and 2 and primarily in the range of 8–20 μm for sample 3. According to Liu et al. [55], the WAD employed in their investigation had a larger size dispersion and a mean particle size of about 80 μm. The samples examined, according to Galindo et al. [52], had a significant percentage of fine particles. According to Wang et al. [50], the particle distributions for the WAD under study are 1.34 μm, 3 μm, and 6.59 μm, respectively.

Chemical Composition of Typical WAD

The claim of WAD containing significant amounts of value metals is supported by Table 1.2, which lists the many chemical species that make up the bulk of these WAD's composition. Al_2O_3 has the largest percentage in each WAD (21.56–82.28%), as one might expect given that aluminum ore is included [52, 55]. SiO_2 (range: 0.38–6.30%), MgO (range: 2.37–4.31%), CaO (range: 1.00–2.80%), and Fe_2O_3 (range: 0.64–1.40%) follow.

The amount of salts employed in the melting process in order to achieve a higher aluminum recovery, according to the researchers, is what caused the high sodium concentration, Na_2O (range: 4.7–21.69%).

Table 1.2 Chemical Compositions of WAD Used in Different Study

Composition	Content (wt. %)		
	WAD 1	WAD 2	WAD 3
Al_2O_3	82.28	75.00	21.56
SiO_2	5.74	6.30	0.38
Na_2O	4.71	2.20	21.69
MgO	4.31	4.00	2.37
CaO	1.00	2.80	1.37
Fe_2O_3	0.72	1.40	0.64
K_2O	0.41	0.70	5.88
TiO_2	0.27	2.80	0.37
CuO	0.25	–	–
MnO_2/MnO	0.13$^{[MnO_2]}$	–	0.05$^{[MnO]}$
ZnO	0.08	–	–
V_2O_5	0.05	–	–
Cr_2O_3	0.04	–	–
NiO	0.02	–	–
P_2O_5	–	–	0.03
S	–	–	2.69
F	–	–	2.89
Cl	–	1.20	24.42
LOI	–	–	21.82
Others	–	3.30	–

Key: WAD 1 = Liu et al. [55]; WAD 2 = Galindo et al. [52]; WAD 3 = Eliche-Quesada et al. [56]

Mineralogy of WAD

Aluminum metal and aluminum oxide were found to be the primary crystal phases in the investigation by Liu et al. [55] using an XRD diffractogram of WAD. Aluminum nitride, aluminum magnesium oxide, and silicon are additional crystal phases.

Morphology of WAD

According to the morphology of the WAD particles utilized in the investigation by Liu et al. [55], they had an irregular form and a rough surface. While many small rod-like particles congregate on the surface of larger particles, some particles have a plate-like shape. On the other hand, the WAD employed in the study by Wang, Xu, and Wang [50] shows that the particles are roughly spherical and the surface is not rough.

1.2.2.3 Recirculation of WAD

A type of WMD having explosive potential [57–59], WAD produced during the production of aluminum goods is categorized as a hazardous waste in many nations [55, 60].

1.2.2.4 Resource Recovery and Recycling from WAD

Conversion of WAD into Value-Added Product As an illustration of efforts to convert WAD into a value-added product, refractory mullite was prepared using WAD from the fine polishing process used in the manufacture of aluminum parts (also known as aluminum buffing dust) [61]. Ball milling was used to combine Ranong kaolin with WAD in a ratio of 100:0 to 40:60. By dry pressing, the batch mixtures were shaped. The temperature used to fire the green specimens ranged from 1100 to 1400 °C.

In the work by Liu et al. [55], WAD was utilized to create autoclaved aerated concrete by acting as a foaming agent, while Eliche-Quesada et al. [56] produced geopolymer foams using the WAD from the secondary aluminum industry's dust filter as a foaming agent. The source of alumina and the foaming agent in this study was WAD. By using a commercial sodium silicate solution and a sodium hydroxide aqueous solution, precursors were chemically activated. The authors claim that the synthetic geopolymer foam materials are equivalent to traditional building products including gypsum boards, foamed concrete, and insulating materials in terms of their qualities. They suggested using these synthetic geopolymer foams as materials for gas filtration or catalyst support in other applications.

1.3 Conclusions

The comparative particle size distribution, chemical composition and morphology results of WID and WAD, provide a better analysis of the possibility of their recirculation or disposal after their stabilization/solidification. Hence, the following deductions were reached:

1. All particle size distribution results show that WID was very fine, with particle size smaller than 5 μm in diameter.
2. The chemical composition of WID produced by steel producers around the world is often identical, with Fe_2O_3 having the highest content (39.56–56.00%), as followed by Cr_2O_3/CrO (9.09–16.30%), then CaO (2.31–14.00%), ZnO (0.93–7.41%), NiO (2.42–6.70%), SiO_2 (4.81–6.42%), MnO/MnO_2 (2.64–5.88%), MgO (2.35–5.44%).
3. The metals in WID were mainly present in the form of complex oxide, and also as silicates.
4. On some occasions, the particle size of WAD ranged between 80 and 105 μm. whereas WAD's PSD was reported between 1.34 and 20 m size fractions.
5. Al_2O_3 makes up the greatest percentage of each WAD (21.56–82.28%), followed by SiO_2 (0.38–6.30%), MgO (2.37–4.31%), CaO (1.00–2.80%), and Fe_2O_3 (0.64–1.40%).
6. Aluminum metal and aluminum oxide were found to be the primary crystal phases in WAD. Aluminum nitride, aluminum magnesium oxide, and silicon are additional crystal phases reportedly present in WAD.
7. The WAD particle shapes range from small rod-like particles with a roughly spherical shape to smooth surfaces.

All of these findings indicate that the WMDs mentioned contain significant amounts of precious metals and other components in addition to hazardous metals. Direct stabilization/solidification techniques for disposal or recirculation were not the most effective ways to manage WMD, though, due to the scarcity of mineral resources. Therefore, resource recovery and recycling from these WMDs is a sustainable strategy from both an economic and environmental standpoint.

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