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Influence of superheated steam flow rate on improved degreasing of oily metal waste

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Abstract. In order to enhance the quality of recycled metal, it is important to remove impurities from waste material. In this paper, oily cutting chips disposed of by metalworking factories are degreased using superheated steam. The degreasing system processes oily waste material continuously under an inert gas atmosphere. An aluminum cutting chip with water-soluble cutting oil disposed from a lace was introduced as a waste material. The degreasing rate depends on the steam temperature, flow rates of waste material and steam, and processing time. In this paper, a demonstration of an oily waste metal degreasing system using superheated steam is constructed, and the influence of steam flow rate on the degreasing rate and energy consumption are experimentally evaluated. As a result, the target adhesion rate, that is less than 1%, was satisfied sufficiently, and the influence of the steam flow rate on the degreasing performance was evaluated.

1. Introduction

The recycling stream for waste material has become a serious issue for the sustainable development of industry and human activity. Waste metal recycling consists of several processes such as scrap collection, compression into bricks, melting and ingot production. Some solid-state recycling systems have been proposed to reduce energy consumption, recycling process and costs [1, 2]. Oily waste metal cutting chips disposed of by metalworking factories is usually melted directly by an electric steelmaking furnace or a blast furnace. However, conventional recycling of cutting chips and scraps produced in the industry has several disadvantages in terms of the adhesion rate of oil and energy consumption. These methods result in low quality metal overall, because an ingredient included in the oil acts as an impurity. Therefore, it is important to remove oil from the waste material. There are some possible methods of removing oil from oily metal waste, such as centrifugal separation, or chemical dissolution. A centrifugal separation method cannot remove oil well enough from metal because cutting chips have a complex shape. On the other hand, if oil is removed with chemicals, the oil is dissolved into a chemical substance and it is then difficult to separate the oil from the chemical agent. In addition, it is also difficult to dispose of liquid waste that includes a chemical substance from an environmentally-conscious standpoint. Accordingly, the systems using superheated steam have been very useful in waste processing. Superheated steam is introduced to improve the quality of recycled waste metal disposed of by metalworking factories [3-5]. The steam evaporates waste oil from oily cutting chips and removes it from the metal.

Superheated steam is a very popular heat source for industrial and municipal applications such as power generation, air conditioning and boilers. It is an inert gas, and this kind of steam creates several industrial advantages for flammable waste material processing. Superheated steam is generated by heating saturated steam until it reaches 100 ºC or higher [6, 7]. Generally, superheated steam shifts to a higher efficiency at around 170 ºC, and is a better fit for industrial applications such as drying moisture materials compared to the efficiency of hot air at the same temperature [8, 9]. The performance and thermal efficiency of superheated steam improves as the steam temperature increases. The influence of steam temperature on the degreasing performance has already been investigated [10]. However, as a matter of course, the energy consumption for the process increases as well as the process temperature increases.

In this paper, a steam circulation-type degreasing system is constructed and the oily aluminum cutting chips were processed. The oily aluminum cutting chips were discharged from lace in a metal working factory. The influence of superheated steam flow rate in degreasing systems on the adhesion rate of oil to waste metal is experimentally examined. The energy consumption supplied to the processing chamber where steam will be heated to the target process temperature will be affected by the steam flow rate. The flow rate is set to two steps. The system's energy consumption and the adhesion rate of oil are evaluated and compared for each experimental condition.

2. System configuration, experimental apparatus and procedure

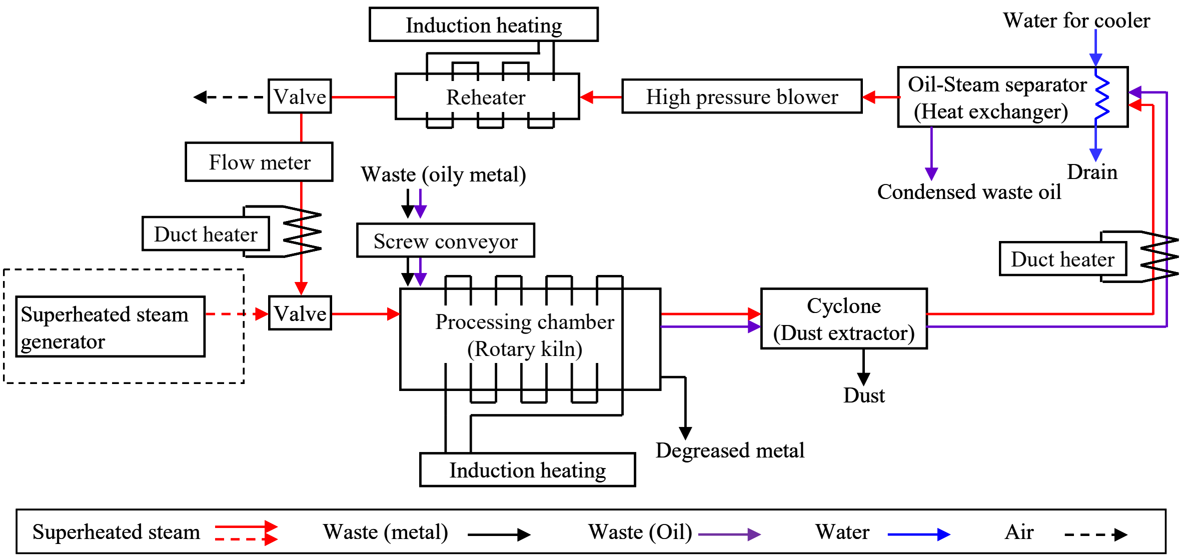
The superheated steam degreasing demonstration system employed in this experiment is shown in figure 1. The system configuration designed for the degreasing system using superheated steam is shown in figure 1(a). The system consists of a superheated steam generator (Fuji Electric; IHSS-05), a screw conveyor, a processing chamber with induction heating (Fuji Electric; HFR200C7K-2), a cyclone, an oil-steam separator, a high pressure blower (Showa Denki; KSB-H07BGHT), a reheater with induction heating (Fuji Electric; HFR5.0C11K-2), a vortex flowmeter (Oval; VXT1040-N11G-1016C) with a flow straightening device installed upstream of a flowmeter, and valves. These pieces of equipment were connected with piping. Here, induction heating was applied to heat the superheated steam and waste materials.

While the superheated steam passes through the processing chamber, oily waste metal is heated higher than the evaporation temperature of cutting oil, while the oil is evaporated under the inert gas field. The pressure inside the processing chamber is almost equivalent to the ambient pressure. Then the mixed gas flows out from the chamber and passes through a cyclone for dust extraction. In the steam circulation-type system, only the evaporated oil is condensed in the oil-steam separator, and steam passes through the separator in a superheated state. Here, the steam temperature is maintained at a temperature greater than 100 ºC. The steam is pressurized using a high pressure blower and heated again by the reheater. After that, the heated steam passes through a flowmeter and flows into the processing chamber when the system is operated in a steady state condition, while the steam that comes from the generator is closed off. In this case, latent heat of the water used to generate steam is not consumed. Finally, the superheated steam can be repeatedly circulated in the degreasing system.

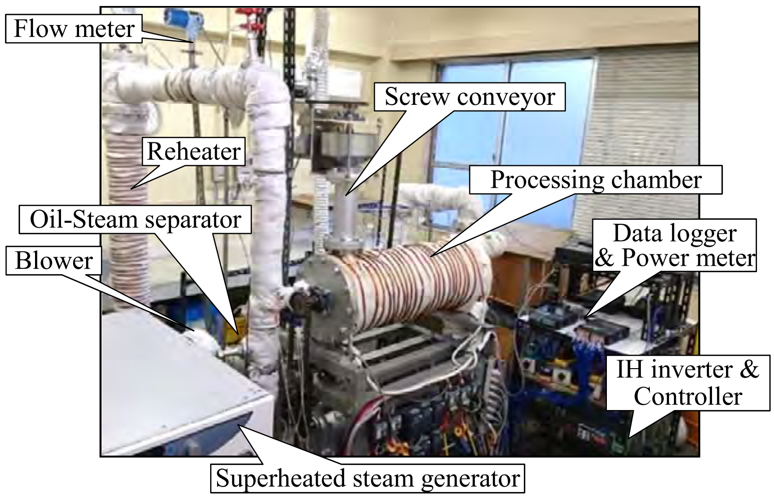
Typical local temperatures in the system are measured by K-type sheath thermocouples and recorded by a multi-channel data logger (HIOKI; 8422-50). The steam temperature inside the processing chamber is an averaged temperature of four local steam temperatures in the chamber. Electric consumption of each piece of equipment is measured by clamp-type power meter (HIOKI; 3169-01).

Figure 1(b) shows a photo of the demonstration system. The size of the processing chamber is 300A (12B) in diameter, 1,000 mm length, and made of magnetic SUS430. The oil-steam separator consists of a radiator to cool steam and two laminated metal screens to trap oil mist. There are steam agitators inside a reheater. The ducts and equipment are covered with a thick layer of heat-insulation material. The waste material is aluminum cutting chips which were discharged from a lace, as shown in figure 1(c). Water-soluble cutting oil without water dilution adheres to the cutting chips. This waste material has a complex shape and encloses waste oil in the gaps.

Before introducing steam to the degreasing system, the steam passage is heated to more than 100 ºC with hot gas in order to prevent the condensation of steam in the equipment and ducts. Hot gas is generated by induction heating and duct heaters, and the gas is circulated by a blower. Then, the processing chamber and steam passage are displaced by superheated steam, which comes from the superheated steam generator. After that, the superheated steam that comes from the generator is closed off, and steam circulates inside the system. Then, the oily waste material flows into a processing chamber. Mass flow rate and processing time of waste material are controlled by revolutions of a screw conveyor and a rotary kiln inside a chamber. The steam temperature inside a processing chamber is controlled by an induction heater installed to the processing chamber. Heat loss from the ducts is avoided by controlling the duct heaters. The practical operation process will be shown in Section 3 with a local temperature progression.



(a) System configuration of degreasing system using superheated steam



(b) Photo of demonstration system

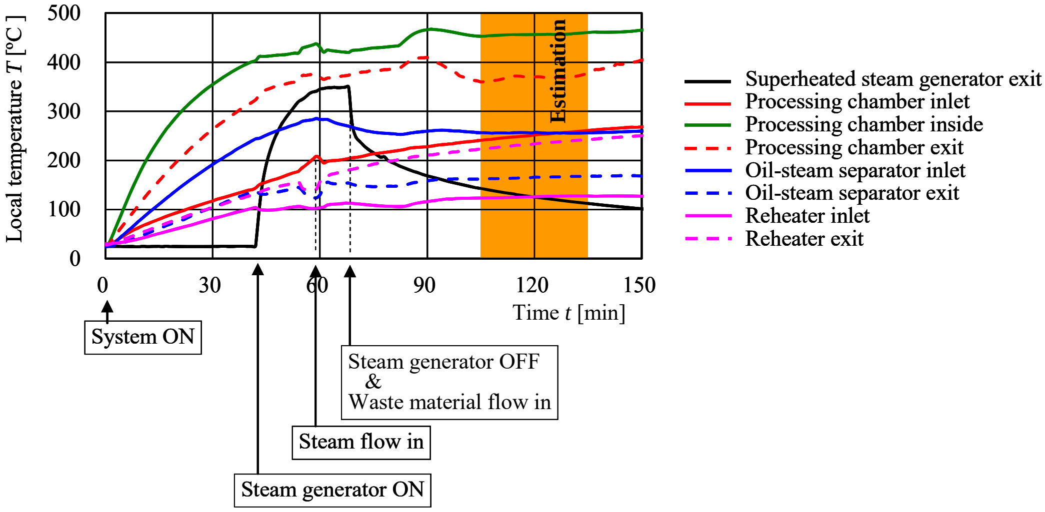
(c) Example of oily waste metal

Figure 1. Superheated steam degreasing demonstration system.

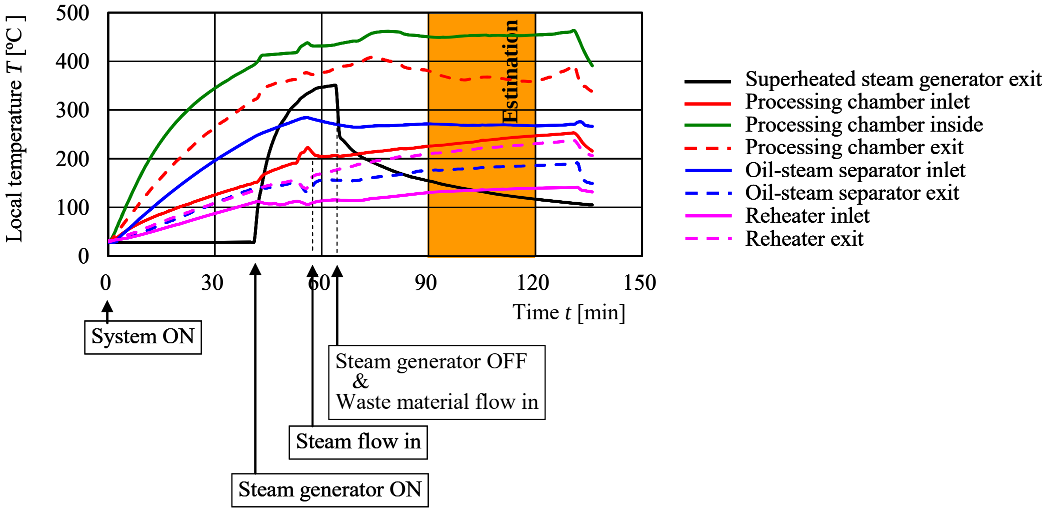
3. Experimental results and discussion

3.1. Experimental conditions and results

The typical progression of local temperatures at each position in the degreasing system is shown in figure 2. Experimental conditions are decided based on the preliminary experiment as shown in table 1. The operation temperature is decided to be 450 ºC class. Higher temperature operation is desirable for the degreasing. However, the waste metal, that is aluminum cutting chips, will melt at around 500 ºC. The steam flow rate chosen here depends on the specification of the vortex flowmeter which can be applied to high temperature steam. The mass flow rate of metal and the processing time result in optimum test outcomes from the preliminary experiments by changing the revolutions of a screw conveyor and a rotary kiln. Mass flow rate of oil is set to 10% of waste metal. Waste metal disposed from metal working factory generally includes around 10% waste oil.



(a) T_P = 450 ºC, Q_S = 27 m^3/h class



(b) T_P = 450 ºC, Q_S = 40 m^3/h class

Figure 2. Progressions of local temperature in each position.

Table 1. Experimental conditions.

Target process temperature T_P (ºC)	450	
Target steam volume flow rate Q_S (m^3/h)	27	40
Mass flow rate of metal M_M (kg/s)	12.7×10^{-3}	13.7×10^{-3}
Mass flow rate of oil M_O (kg/s)	1.27×10^{-3}	1.37×10^{-3}
Estimated processing time of oily metal in the chamber t_C (min)	6.0	

At the beginning of the experiment, each piece of equipment and the ducts were heated by hot air in order to prevent condensation of the superheated steam inside the system. The electric consumption of each piece of equipment was set the same, except for the induction heating of the processing chamber. The air temperature in the system increased gradually. It took about 40 minutes to heat the system to over 100 ºC, which is the evaporating temperature of water. Then, the superheated steam generator was started and steam was introduced into the system. Here, the temperature of the steam exiting the superheated steam generator was around 350 ºC. After the air, which contains oxygen, was displaced from the processing chamber by superheated steam, the steam generator is stopped and steam is circulated inside the system by switching the valve. In this case, superheated steam was circulated inside the system by blower. Then, the waste material flowed into the processing chamber, and the degreasing was started.

Local temperature and electric consumption were estimated from extracted data for 30 minutes in the steady state condition, as shown in figure 2. Average local temperatures at the steady state condition are shown in table 2. The pressure inside the processing chamber was almost equivalent to the ambient pressure.

Table 2. Average local temperatures at the steady state condition in each operation condition.

Steam volume flow rate class (m^3/h)	Q_S	27	40
Steam volume flow rate (m^3/h)	Q_{Sr}	27.1	37.5
Superheated steam generator exit (ºC)		closed	
Processing chamber inlet (ºC)		251	237
Processing chamber inside (ºC)	T_{Pr}	456	452
Processing chamber exit (ºC)		369	367
Oil-steam separator inlet (ºC)		256	270
Oil-steam separator exit (ºC)		165	181
Reheater inlet (ºC)		126	136
Reheater exit (ºC)		233	221

During the degreasing process, the average temperature inside the processing chamber was maintained at around 450 ºC. The lowest steam temperature was kept over 100 ºC during the degreasing operation. Additionally, the steam temperature at the oil-steam separator exit was kept at around 150 ºC because the specification of evaporation temperature of the cutting oil is around 150 - 250 ºC.

The influence of the steam flow rate on system performance was evaluated in terms of its electric consumption and the adhesion rate of oil.

3.2. System performance of degreasing conditions

The degreasing performances were compared. Table 3 and figure 3 show the adhesion rates of oil to waste metal at each operation flow rate. The rates, ζ_{before} and ζ_{after}, were estimated for before and after processing by equations (1) and (2), respectively.

$$\zeta_{before} = \frac{\rho_{oil} - \rho}{\rho} \times 100 \tag{1}$$

$$\zeta_{after} = \frac{\rho_{deg} - \rho_w}{\rho_w} \times 100 \tag{2}$$

Here, ρ and ρ_w are bulk densities of the metal without oil, while ρ_{oil} and ρ_{deg} represent the bulk densities of the waste metal including oil. ρ_w was estimated by washing the waste material with water after degreasing, in order to estimate only the mass of the metal. The waste material before and after processing are put into a container with a fixed capacity, and their weights were measured with a balance. The weights are measured three times in each step. Then, the bulk densities are estimated by the weight and its capacity. The waste metal was slightly compressed during the processing, because the waste metal was transported in a rotary kiln. Therefore, the bulk densities of the waste material after degreasing increase rather than those obtained from before processing, and the accuracy of the balance influences the bulk density. Therefore, the adhesion rate of the oil must be individually estimated before and after the processing.

Initial adhesion rates were set at around 10% in these experiments. After the degreasing, the rate decreased to 0 - 0.2% under each condition. The final target of the adhesion rate of oil is set to be less than 1% and was achieved by these experiments. This target is difficult to achieve by compression or centrifugal separation methods.

Table 3. Bulk density and adhesion rate of waste material in each condition.

Steam volume flow rate Q_{Sr} (m^3/h)	27.1	37.5
Process temperature T_{Pr} (ºC)	459	455
Metal ρ (kg/m^3)	582	540
Oily metal ρ_{oil} (kg/m^3)	640	594
Degreased metal ρ_{deg} (kg/m^3)	580	557
Metal (After washing) ρ_w (kg/m^3)	580	556
Initial adhesion rate ζ_{before} (%)	10.0	10.0
Degreased adhesion rate ζ_{after} (%)	0.0	0.2

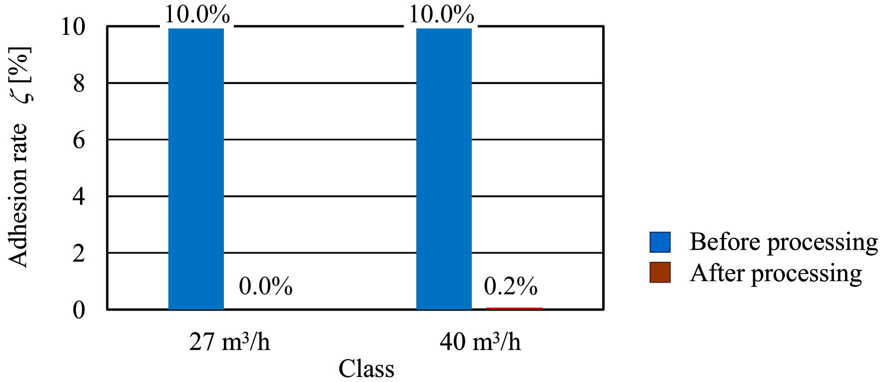


Figure 3. Adhesion rates of oil in each condition.

Estimates of electric consumption from each operation temperature were compared. Table 4 and figure 4 show the amount of electric consumption in the steady state condition in each flow rate condition. The electric consumption for the high pressure blower, micro-heater heating for the ducts, conveyance systems, and supplementary equipment were set the same under each condition. Supplementary equipment refers to the screw conveyor, rotary kiln in the processing chamber, and steam agitator in the reheater. Therefore, the differences in electric consumption between these conditions are thought to have been caused by induction heating of steam, because the mass flow rates of the waste were almost the same, as shown in table 1.

Table 4. Electric consumption in steady state condition.

Steam volume flow rate Q_{Sr} (m^3/h)	27.1	37.5
Process temperature T_{Pr} (ºC)	459	455
Induction heating for Processing chamber (kW)	10.2	11.0
Induction heating for reheater (kW)	2.8	2.8
Blower (kW)	0.2	0.2
Duct heaters (kW)	1.0	1.0
Supplement equipment (kW)	0.2	0.2
Total E (kW)	14.4	15.2
Specific energy consumption (kWh/kg)	0.27	0.34

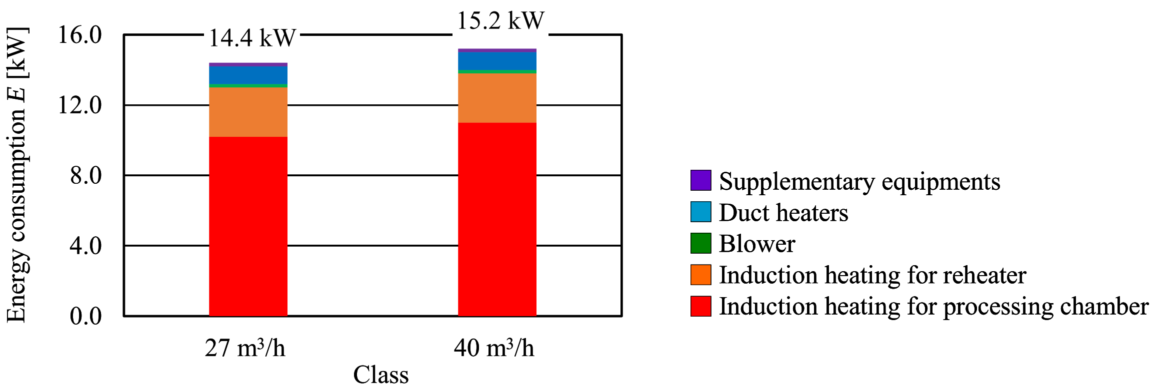


Figure 4. Electric consumption in steady state condition.

The energy consumption of induction heating for the processing chamber was increased to maintain the mean temperature T_{pr} in the chamber. About 70% of the total energy is consumed by induction heating installed in the processing chamber. The electric consumption of induction heating for the processing chamber increases less than 10% even though the steam flow rate increases by approximately 40%. The influence of the steam flow rate on the electric consumption is relatively small, but increases. As a result, electric consumption is decreased as the steam flow rate decreases, because the steam temperature in the system is almost the same. The specific energy consumption decreases as the steam flow rate decreases, too.

4. Conclusion

The performance of a practical steam circulation-type superheated steam degreasing system was evaluated for several steam flow rates. Here, the performance was evaluated based on the adhesion rate of oil and the specific energy consumption for the waste material. The adhesion rate is reduced considerably in each experiment and the target rate was well satisfied. The steam flow rate in the processing chamber does not strongly influence the energy consumption. However, the reduction of the steam flow rate suggests a reduction of energy consumption.

The adhesion rate of the oil after degreasing is influenced by process temperature, mass flow rates of steam and waste material, and processing time. Therefore, it is important to harmonize these relations for the optimum operation.

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