# COLD COMPRESSION IN DIRECT RECYCLING OF ALUMINIUM 6061

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## ABSTRACT

In conventional recycling method, the aluminium scrap undergoes melting process whereby only 52% of the aluminium are recycled and the others are wasted in terms of melting loss, dross, extrusion scraps and etc. Other than material loss, the energy usage needed for conventional process are very high with energy consumption of 6000 kcal/kg and high operation costs due to the large number of operation. This research focus on one of the least researched direct recycling method that is by cold compression. Only one optimum chip size was used, that is (4-6) mm x (3.5-4.5) mm x (1.45-1.55) mm. The chips were cold compressed with a Force (F) of 35, 40 and 45 tons with variable in Holding Time (t = 1, 5 and 10 minutes). The compressed samples were then placed into the furnace to be sintered at different Temperature (T) namely, 0 ℃ (no sintering), 500 ℃ and 600 ℃. Both the mechanical properties (Ultimate Tensile Strength, UTS and Elongation to Failure, ETF) and the physical properties (Density, D and Micro-hardness, MH) were then tested. Response surface methodology (RSM) was then applied to identify the optimal variable parameters for specific goals. It was found that an increased in the compression force above the optimum condition will not bring any significant outcome on the compressed specimen. Whereas, sintering process increases the UTS to maximum of 14.67 MPa at sintering temperature of 600 ℃. But at the same time, the specimen that was sintered at 600 ℃ show low ETF of only 1.23%. As for specimen that were not sintered (0 ℃), the lowest recorded UTS is 2.77 MPa but having better micro-hardness that was even higher if compared to the reference specimen with micro-hardness of 117.10 HV. Even though there is an improvement in mechanical and physical properties but the microstructure of the sample reveal that there is lack of bonding in the structure as the chips were more to overlapping each other rather than inter-locking one another. Further improvement in terms of shear deformation like hot extrusion is highly recommended to ensure better material bonding and powder metallurgy may be one of the other ways to strength the recycled chips as powdered aluminium sintered better than aluminium chips.

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# LIST OF SYMBOLS AND ABBREVIATION

| | | |
|---|---|---|
| $V_c$ | - | cutting speed |
| *f* | - | feed |
| d | - | depth of cut |
| F | - | compression force |
| T | - | sintering temperature |
| t | - | holding time |
| MP | - | Mechanical properties |
| D | - | Density |
| MH | - | Micro-hardness |
| HSM | - | High speed machining |
| RSM | - | Response surface methodology |
| UTS | - | Universal tensile strength |
| ETF | - | Elongation to failure |

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# CHAPTER 1

# INTRODUCTION

In the twenty-first century, one of the key factors that is to be taken into consideration is the weight of the material used. Therefore, light metals are the key application for automotive and aerospace industries in the twenty-first century to manufacture light and efficient transport vehicles.  Nowadays, aluminium and aluminium-alloys are often used in both automotive and aerospace industries due to its low density and good mechanical properties (Panke et al., 2013). Other than that aluminium is one of the most abundant metal in the Earth's crust and most widely used material after steel, but the at the same time the production of aluminium is the most energy intensive process and requires almost 200 GJ/ton which is almost 10 times of that required for steel production. Aluminium can either be produced from bauxite ore to produce primary aluminium or by re-melting aluminium scrap to produce secondary aluminium which requires about 10 GJ/ton that comprises of 5-10% of the energy needed for primary aluminium production. In the year 2000, the global aluminium production was about 33 million tons, of which 8.5 million tons were secondary aluminium. This shows a recycling rate of 26% and it will be increasing in the years to come. Thus, it is expected that the recycling rate will reach 50% by 2030 (Guley et al., 2010).

When metal products are manufactured, considerable amount of waste is produced, whether it is the form of chips or scraps (Gronostajski et al., 2000). Chips, particularly those derived from the machining operations are usually characterized by irregular elongated and spiral shape (Gronostajski et al., 1996; Fogagnolo et al., 2003; Gronostajski et al., 2001). This waste and scraps can be returned to be melted,

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whereby some of the metal is recovered and reutilized in production processes. During the recycling of the waste and scrap, a lot of metal is lost as a result of oxidation and there are extra costs of labor, energy as well as the expenditures on environmental protection which increases the general cost of the process. There is a different way of recycling metal chips which was introduced and patented by Stern in 1945 (Misiolek et al., 2012). This method contains the cutting of chips to a granulated product that is then cold-pressed and hot extruded or hot forged, whereby melting is eliminated from the recycling process.

## 1.1 Conventional recycling

Aluminium chips from machining of semi-finished products which are usually characterized by their elongated spiral shape and small size in comparison with other scraps are probably most difficult to recycle by conventional methods. This is due to the average material loss of 20% during re-melting process which cannot be avoided as the aluminium chips have a high surface area to volume ratio; contain contamination with oxides, machining oil and etc. Whereas, in the case of tiny chips material loss can reach up to 50%. Since the 1980s there have been several efforts to increase the energy efficiency of melting furnaces. Although these efforts improved the melting process considerably, the energy consumption for secondary aluminium production can still reach up to 20 GJ/t depending on the condition of aluminium scrap, production facilities and process (Guley et al., 2013).

In the process of melting aluminium and aluminium-alloy chips, on average about 10% of the metal is burnt and about 10% of it is lost because aluminium mixed with the slag are removed from the surface of the ladle. The losses are irreversible and can reach up to 35% if smelted with gas or oil-fired furnace instead of induction furnaces. Whereas the main cause of the substantial losses of aluminium and aluminium-alloy chips during conventional recycling is its low density due to which it stays rather long on the surface of the molten metal and oxidizes intensively. Further losses can be seen during casting, in the form of various discards such as risers, shrink holes and so on, which reach about 8%. Later, there are losses amounting about 18%, during the processing of the casted aluminium and aluminium-alloys (rolling, extrusion and forging). Therefore, ultimately there are no more than 54% of the metal is recovered with a total energy consumed amounting

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16-19 GJ/tons (Tekkaya et al., 2009) (Gronostajski et al., 1997) (Samuel, 2003). The summary of the losses of material and the final recycled products is shown in Figure 1.1. Other costs included labour cost which total amounted to 11-15 man hour per ton. These include, 3 man hours per ton for production of ingots, 5 man hours per ton to produce billets and 3-5 man hours per ton for production of section.

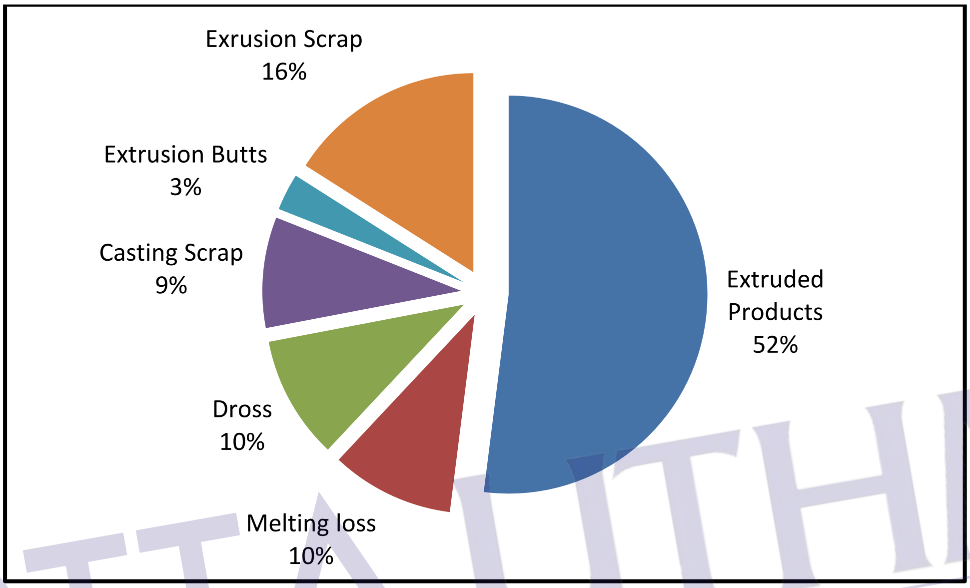


Figure 1.1: Material losses in conventional recycling (Samuel, 2003)

## 1.2 Direct recycling

To avoid re-melting the aluminium chips, a technique of using hot extrusion process was invented to direct recycle the aluminium chips. This concept was introduced and patented by Stern in 1945. Direct recycling method also known as solid-state recycling is proposed as a new method of recycling, where by the chips are recycled by consolidation using plastic deformation processes such as cold and hot forging followed by hot extrusion, and by microstructural control such as grain refinement and dispersion of oxide precipitate (Hu et al., 2008). This method is possibly due to the joining of the aluminium under high pressure, high strains and temperature just below the melting temperature. The occurring strains result in a cracking of oxide layer. The high pressure and temperature lead to join caused by contact of the surface of the pure aluminium. The process is similar to at the seam-weld formation when extruding hollow profiles with porthole dies (Panke et al., 2013).

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The aluminium chips undergo different processes in the direct conversion of aluminium chips into compact metal by granulation, premolding and hot extrusion or hot forging, where smelting is eliminated. During the whole process of direct conversion of aluminium chips into compact metal by extrusion, the waste is a part of the chips from which impurities cannot be removed, amounting to about 2% and the extrusion waste of up to 3%. Thus, ultimately 95% of the aluminium chips are recovered.  The direct conversion of aluminium and its alloys chips were reported to produce  good materials, characterized by low porosity, relative density exceeding 95%, high hardness and good tensile properties and only slightly lower than those metallurgically produced materials. The number of process to recycle the aluminium chip has been reduced as shown in Figure 1.2. The energy needed is only 5-6% GJ/ton which is only 5-6% of that needed for the conventional process chain that include a re-melting phase to produce new extrusion billets. Other than that, the reduced operation allows labour to be reduced to 2.5-6.5 man hours per ton of the product (Pantke et al., 2013; Gronostajski et al., 2010; Tekkaya et al., 2009).

Other benefits of direct conversion of aluminium and aluminium-alloy chips into compact metals include the possible reduction in the funds spend on environment protection as a result of the reduced consumption of ores and energy carriers, and less degradation of the natural environment because of reduced air-pollution emission. Since the whole recycling process is conducted in the solid state, there is no need to have a special protective environment to undergo this process or no extra caution is needed to be taken. Recycling aluminium and aluminium-alloys by direct recycling method is relatively simple, so the whole process consumes small amounts of energy and does not harmfully affect the environment (Gronostajski et al., 1997).

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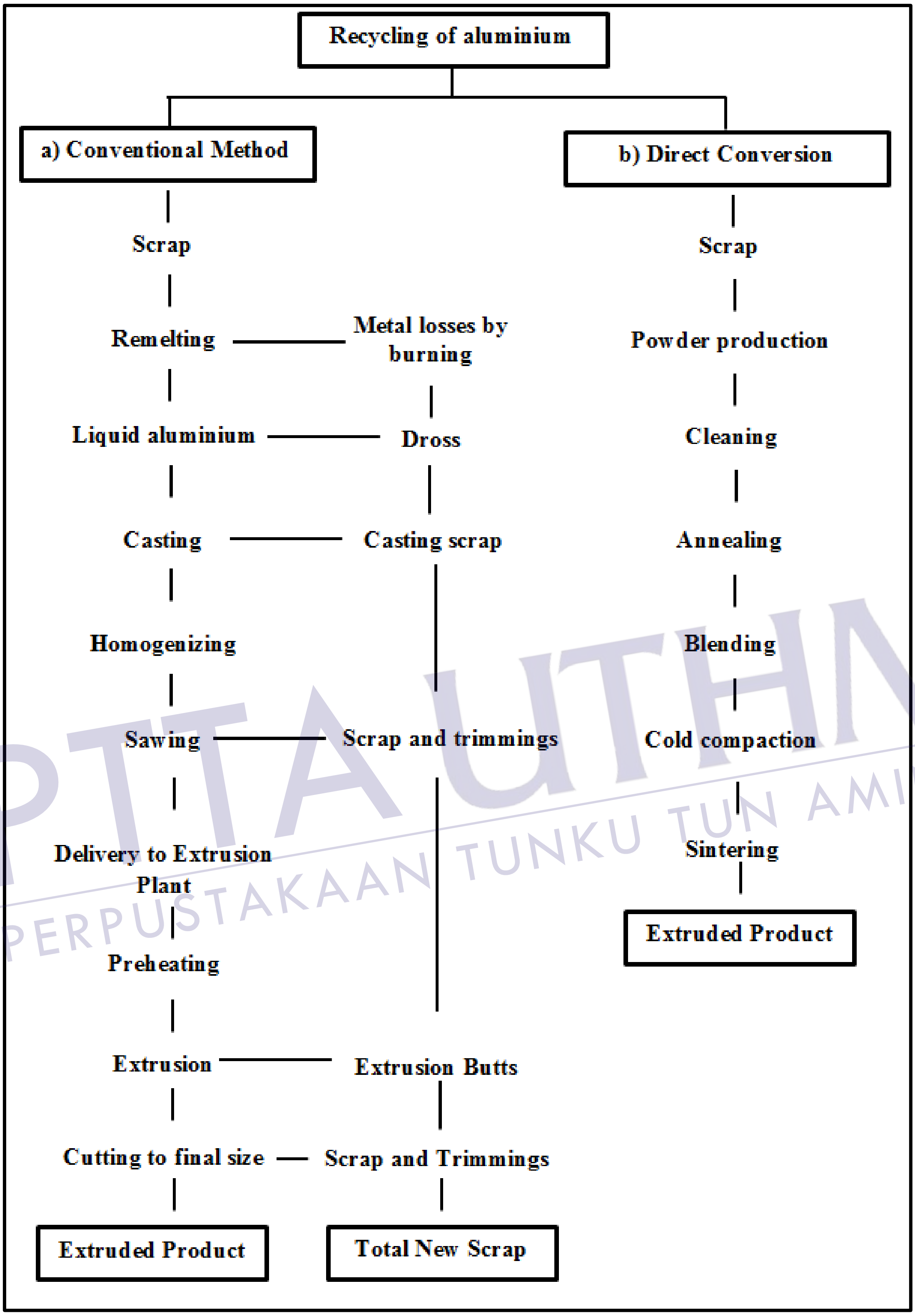


Figure 1.2: Flow chart of recycling of aluminium of scraps (a) Conventional method (b) direct conversion method (Samuel, 2003)

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## 1.3 Problem statement

Reycling of aluminium scrap has been widely practiced in many countries to reduce the wastage of natural resources. The aluminium scraps are required to undergoes the remelting process during the recycling process when conventional method has been implemented. However, due to the high temperature needed to completely remelt the aluminium scraps, there is a high consumption of energy with high operating cost. Due to the natural shape of the alumnium scraps of high-speed machining, their small and elongated spiral shape leads to easy evaporation of the material into the atmosphere which leads to loss of precious materials. So direct recycling or solid state recycling is introduced and able to recycle the aluminium scraps without undergoing the remelting process. Thus, the usage of energy and the loss of material are reduced during the recycling process. Currently there are a few direct recycling techniques being developed, namely hot extrusion, powder metallurgy, hot forging and cold compression. Here, the focus will be on the uses of cold compression in direct recycling. Cold compression technique has not been researched much before particularly on mechanical and physical properties, as well as in the microstructure of the compressed sample. Hence, to further research on this technique, the data on mechanical and physical properties and the microstructure will be invertrated. Parameters such as chip size, compression force, number of compression and holding time are to be considered to enable higher quality of compressed aluminium,. Most research studied the effect of chips size, number of compression and compression forces but parameters such as holding time and sintering temperature after compression are rarely seen to be done. Therefore, by looking deeper on these parameters, new findings may contribute improvement and thus, perfecting of this technique can be done.

## 1.4 Significance of study

As compared with the precious research on cold compression of aluminium chips, there are a few or no research that study the effect of sintering after compression process and the holding time during the compression process. So to be able to understand more on the potential of cold compression in the field of direct recycling such parameter should not be left untested. Since the heat is not introduced in cold

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compression technique, post processing such as sintering may help strengthen the compressed aluminium as heat soften the aluminium and enable better bonding between the aluminium chips. On the other hand, holding time which enables a compression force to be applied to the chips of a set amount of time may help retain the structure of the compressed aluminium and to ensure the chips are fully compacted.

Studies on these parameters will contribute to a new knowledge of cold compression on recycling aluminium chips, where it may influence the temperature used, time taken and even the outcome of the compressed aluminium. This will be helpful in determining the optimum parameter of cold compression in aluminium chips where there will be less wastage of energy, time and may be helpful as pre-process for extrusion as sample preparation. This study will help to bring recycling of chips through hot extrusion one step closer to be used in the industries.

## 1.5 Purpose of study

The project is undertaken to study the process of direct recycling method (cold compression) to improve this technique for more efficient recycling of aluminium (AA6061). The objectives are:

i. To determine the relationship of the effect of various holding time for compression (t), sintering temperature (T) and compression force (F) on the compressed recycled aluminium responses specifically on mechanical properties (MP) and physical properties (PP).

ii. To identify the significant parameter of compression force (F), sintering temperature (T) and holding time (t) over mechanical properties and physical properties responses by employing Response Surface Methodology (RSM).

iii. To make a comparison and recommendation based on mechanical properties and physical properties for both recycled and original unprocessed of aluminium AA6061.

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## 1.6 Scope of study

In order to successfully realize the objectives of the study, the following scope of works have been set:

i. Using 6061 aluminium-base composite chips and using the same mechanical properties for the original 6061 aluminium-base composite (as-received) as a comparison.

ii. Compression done in three different holding times namely 1, 5 and 10 minutes.

iii. Size of chips used is 5 ±1 mm x 3 ±0.5 mm x 1.5 ±0.05 mm

iv. Conducting cold-pressed in 5 mm x 100 mm die with compression forces of 35 tons, 40 tons and 45 tons respectively.

v. Compressed aluminium specimen is sintered in box furnace for 1 hour.

vi. Sintering temperatures used in this study will be at 0 ℃ (no sintering), 500 ℃, and 600 ℃

vii. Comparing and analyze the following response:

   a. Tensile properties that include ultimate tensile strength (UTS) and elongation to failure (ETF) using Universal Testing Machine.
   b. Micro-hardness at deeper layer of the surface using Vickers Hardness Tester.
   c. Density of the specimen using Density balance machine.
   d. Microstructure characteristics using Optical Microscope (Olympus BX60M)

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## 1.7 Hypothesis

Studies on the effect of sintering temperature, compression force and holding time need to be done, as these parameters were not thoroughly been investigated. This study will provide findings that will help to perfect direct recycling technique of aluminium chips as well as bringing direct recyling a step closer to industrial use.

It is undeniable that temperaure do play a huge role in recyling of aluminium. So to find out the optimum sintering temperature will be of great importance as temperature usually have a close correlation with the mechanical properties and the physical properties of the compressed alumnium. Other than that in an industry, time taken for each process have to be carefully calculated as the production rate is highly influenced by this factor. Hence, having an optimum holding time for cold compression will save time. The same goes for the compression force during the cold compression process. An optimal selection of parameters enable to satisfy an economic objectives which are maximizing production rate and minimizing production cost.

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# CHAPTER 2

# LITERATURE REVIEW

Literature review plays an important role to seek a new and quality research development in the particular field of study. This chapter reviews comprehensively about the direct recycling method in recycling chips, particularly on the variable parameters that was used. Beside, this chapter also reviews on the methods selection that was used before and during the direct recycling process. The beginning section explores the process of cold compression as pre-process in extrusion and the significant of cold compression beforehand, and then followed by the review on cold compression as direct recycling process in term of relative density.

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## 2.1 Cold compression as pre-processing in extrusion

Both chip size and billet preparations are important factors that should be highlighted in preparing for hot extrusion process. As a "solid" billet is achieved when interlocking of the chips can be seen after the compacting process at room temperature (Tekkaya et al., 2009) and the billet is dependence on both the chip geometry and compacting process parameters to show any structural stability due to interlocking of the chips (Panke et al., 2013). Tekkaya et al. (2009) tested the recycling of chips according to 3 different chips size, namely (>30) mm x (6-8) mm x (0.5-1.5) mm, (>30) mm x (1-2) mm x (<0.2) mm and (<10) mm x (4-6) mm x (<0.2) mm and categorized as type A, B and C accordingly. Each type of chip was produced through turning but with different cutting speed, $V_c$, feed, $f$ and cutting depth, $a_p$ as shown in Table 2.1. In order to increase the density of the billet, up to 7 compacting steps were taken to produce one billet with a length larger than the minimum billet length of 88 mm. From this experiment, it was found that the influence of compacting process is negligible when a high pressure, temperature and strain level during extrusion process is guaranteed. Other than that, it can be seen that the extrusion process was independent of the chip geometry and chip production.

Table 2.1: Parameter of machining for different chip size

| Type of chips | Tool | Cutting Speed, $V_c$ | Feed, *f* | Cutting Depth, $a_p$ |
|---|---|---|---|---|
| | | mm/min | mm | mm |
| A | Turning | 175 | 0.004 | 8.0 |
| B | Turning | - | - | - |
| C | Milling | 280 | 0.005 | 30.0 |

Hu et al. (2008) who conducted a similar experiment on effect of chip size on AZ91D magnesium. The chip size that used were (4-6) mm x(3.5-4.5) mm x(1.45-1.55) mm, (10-16) mm x (1.8-2.2) mm x (0.48-0.52) mm and (5-8) mm x (1.8-2.2) mm x (0.18-0.22) mm. It was found that chip size with (4-6) mm x (3.5-4.5) mm x (1.45-1.55) mm shows a good combination of higher ultimate tensile strength of 340 MPa and higher elongation to failure of 10.5% compared to an as-cast specimen. Hu et al. (2008) has also taken the oxygen content of the extruded material and found that oxides in the recycled (extruded) specimen contribute to higher tensile strength and elongation to failure. But excessive oxide can adversely affect the elongation to failure as it may prone to cause an early development of micro-voids which leads to lower elongation. The two stated contributor was the increase grain size where the accumulated oxygen concentration increases linearly with the total surface area and the increased oxide precipitation which was primarily introduced from the machined chip surface.

Another research done by Pantke et al. (2013) on two different materials with two different chips size that were used. The material that were used in this research are AA7175 and AA7475 aluminium and the chips size is categorized into chips produced for industrial rough machining process and a finishing process with different depth of cut. The depth of cut of chips from industrial machining process is 2 mm and 10 mm for chips from finishing process. Then the chips undergoes

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