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TEMPERATURE-CONTROLLED NEW DIE MODELLING IN ALUMINUM (6061) EXTRUSION AND ITS COMPARISON WITH CONVENTIONAL DIES BY USE OF FEM ANALYSIS

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Abstract: In conventional extrusion processes, inability to keep especially the billet at the intended heat treatment temperature leads to waste of material and energy as well as dimensional linearity problems. In our study, an extrusion process involving a newly designed Resistance Container for extrusion of A16061 alloy has been modeled by the help of finite element (FE) method and compared with conventional extrusion dies. With the designed resistance container model, billet temperature was raised to extrusion temperature (550°C) in 30s and the process was conducted at this temperature in 336cm3 volume. In conventional model temperature is 200C but at new designed model 500C. Temperature reduction that occurred at a rate of 50% in the case of conventional extrusion processes has occurred at around 10% in our model. Extrusion force is decreased from 294MPa to 114.7MPa thereby resulting in minimized values of associated pressure and stress.

Key words: Resistance Container, Al6061, Aluminum Extrusion, Hot Extrusion, Forming.

1. INTRODUCTION

Al extrusion is one of the current methods employed to produce profile sections. High dimensional accuracy and good surface quality of long profile sections in particular engender the necessary conditions for extrusion of Al alloys. To satisfy these conditions, certain parameters such as mechanical properties of the billet, temperature, and ram velocities must be selected correctly. In the case of conventional production methods, incorrect selection of extrusion parameters is likely which, in turn, results in reduced process performance, decreased efficiency, and increased product cost, [1]. In extrusion processes, temperature rise which appears to be the most important parameter of the process may be controlled by changing the velocity of the ram instead of changing process parameters on the basis of press force only, [2]. Temperature rise varies at the outlet of the container (in the plastic deformation zone) and different temperature fields build up at certain areas, [3]. This situation leads not only to surface deformation of the part fabricated and production of defective parts but also to waste of material at significant rates. In studies conducted with respect to aluminum and lead extrusion, different dies have been used to research surface quality of alloys and especially the flaws on their surface, by the help of upper bound method, [4]. Furthermore, in a similar study involving the use of 3D FEM model, it was established that temperature variation at the outlet of the container was between (100-430)^{o}C, [5]. Pressure caused by temperature has been studied in fabricated parts containing Ti alloy with particular emphasis on the relationship of such strain with parameters such as density of material, change in grain structure, and heat transfer [6-7] Grain structure of the billet which changes during extrusion process is of prime importance as it would result in changed mechanical properties of the product following the process [8-9]. Grain structure of silicon-rich AlMgSi alloy and its phase transformation after the extrusion have been investigated [10]. Stresses to occur during the process bear significance in terms of the quality of the end-product. Stresses ranging from 20:1 to 60:1 with reference to extrusion rate of Al6061 alloy and form of changes in mechanical properties of the parts fabricated have been experimentally studied [11-12]. Different profile sections in Al extrusion process and temperature in wire drawing at different rates qualify as important process parameters [13].

Conducting modeling studies prior to fabrication of industrial components helps minimizing waste of time, material and labor [14]. Our study has included FEM analyses in regard to the extrusion process involving a newly designed and suggested heated container. In this framework, a model that is considered to be a good alternative to conventional methods and which would enable the saving of time, labor and energy has been developed. Thanks to this different design, it will be possible to manufacture wire drawing products and profile sections through a fabrication process where temperature and associated grain structure and mechanical properties may be controlled. Keeping the temperature under control will help minimizing temperature-related problems, such as grain structure in particular, thereby ensuring the conduct of extrusion processes in a much more controlled fashion.

2. MATERIALS AND METHODS

FEM Modeling

FEM-MSC Simufact 10.1 software has been used to show temperature distribution of heater modified (resistance) container in aluminum extrusion. Resistor housings for the heaters have been provided in the container. Number of these housings is 22 ea in the upper part and 15 ea in the lower part (in the narrowing section). For the container, slMesh Tetra and Tetrahedral (134) elements have been used. Element size is 4.6115 mm whereas number of elements is 128,086. Resistor housings have been meshed with slMesh Tetra.

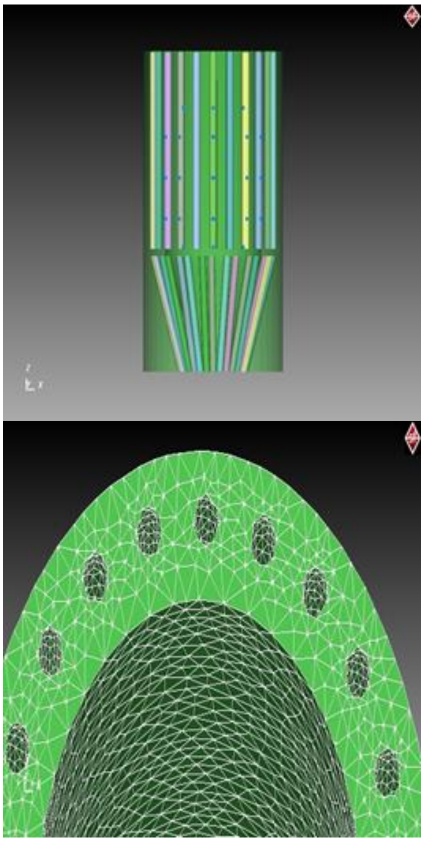


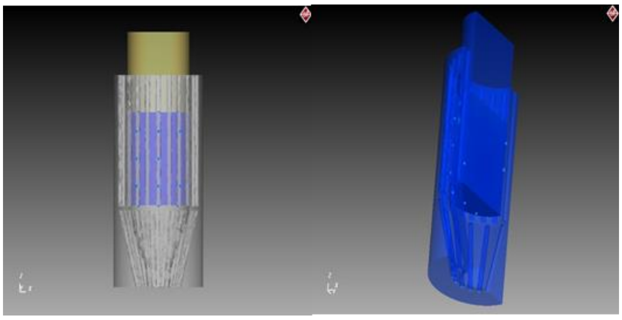
Fig 1. Location of the points on workpiece (a) and meshing (b)

In Fig 1.a, mesh elements for the billet have been selected as slMesh Tetra and Tetrahedral (134). Element size is 3.279mm and 32,565 ea elements have been used for the container (Fig 2.b). A refinement zone has been established for the container where plastic deformation occurred and also for the billet in the container. Materials defined are toolsteel for the container and the press, AA6061 (T= 250-500°C) for the workpiece, and Zirconium (T=600-1000°C) for the heater resistors (Table 1) (MSC materials library 2012). At the first step, the billet has been heated by means of resistors mounted into the container in the newly designed model, before commencement of the extrusion process (Fig 1a). FEM analysis of the heating process has been conducted in MSC Simufact 10.1 software. Zirconium (600-1000°C) resistors energized by electric power may give off a temperature around 900-1000 oC. For this reason, zirconium resistors have been used for the heating process, which were modeled in a manner to give off an average temperature of 900°C. Heating time has been realized at an interval of 70s so as to achieve a homogeneous (uniform) billet temperature.

Table 1. Mechanical properties of the materials used in FEM analyses

Mechanical Properties	AA6061	Tool steel	Zirconium
Young Modulus	36.81 MPa	189 GPa (T= 573 °C)	94.5 GPA
Poisson’s Ratio	0.333	0.3	0.34
Density	2640 kg/m^3	7850 kg/m^3	6530 kg/m^3
Thermal Expansion	2.8e-005 °C	1.2 1/°C	6.9e-006 1/°C
Thermal Conductuvity	193 W/m °C	6.05 W/m °C	16.7 W/m °C
Specific Heat Capacity	1132 J/kg °C	434 J/kg °C	285 J/kg °C
Tensile Yield Strength	310 MPa	250 MPa	100 MPa
Compressive Yield Strenght	-	-	167 MPa
Tensile Ultimate Strenght	560 MPa	460 MPa	-
Elasticity	69 GPa	-	-

At the second step, all mechanical properties of the billet heated to the extrusion temperature, which have changed as a result of the heating process, were dwelled on together with the billet itself (Fig 2 a-b). Certain changes occur in physical and mechanical properties of the billet during heating. Therefore, it is necessary for a realistic modeling to introduce the new mechanical properties to FEM program during transition to the second phase (extrusion process) following the placement of the heated billet into the container or heating of the billet in the container. Such changes should be defined in the model for the heat treated billet before undergoing the extrusion process. In extrusion process, a hydraulic press with 80 mm/s ram velocity has been defined within the scope of a developed model with an average friction value of m= 0.07 coulomb. In this model, contact table has been formed for each resistor and between container-billet, container-punch, punch-billet, and near contact reference value has been considered as 0.1 mm.



a. b.

Fig 2. Extrusion process model of Al6061 alloy
a. Front View b. Section

container too is heated in the heating chamber). However, since heat transfer between hot billet and cold container is very high, the billet should be heated to a temperature in excess of the extrusion temperature so that a sufficient extrusion temperature may be attained even if heat transfer occurs in the case of contact with the container. In conventional methods, the billet heated to the extrusion temperature (or to the next higher degree) is placed into the container. Another conventional extrusion method involves heating of the container in the

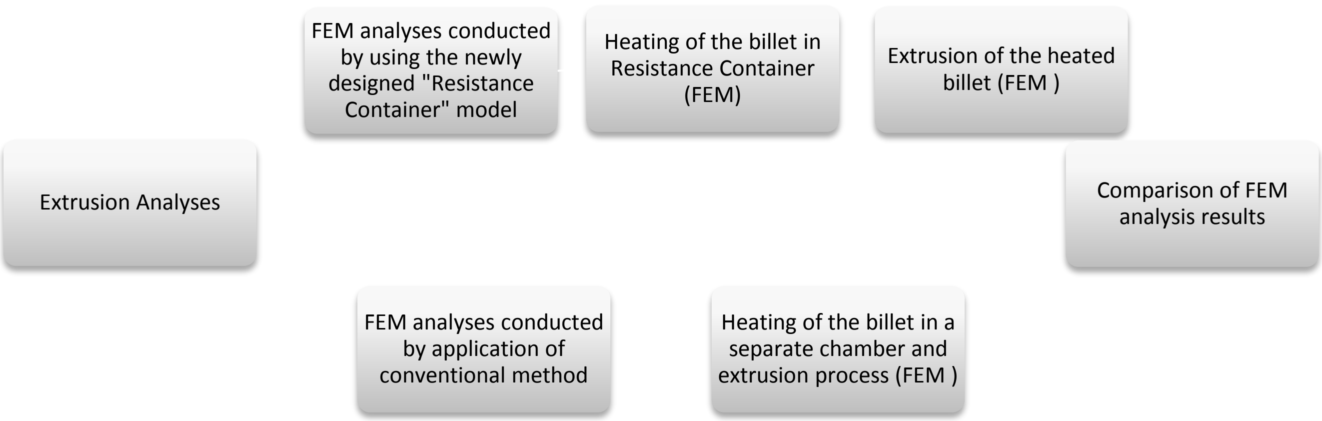


Fig 3. Flow Chart of FEM Analyses

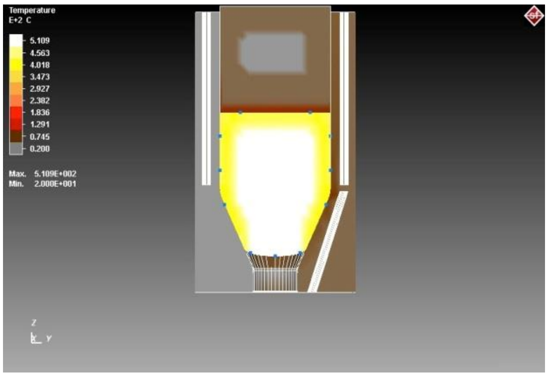
In the case of conventional extrusion processes involving an unheated container, temperature is considered as 550°C and the billet is manually heated slightly above this temperature. On the other hand, in the case of this newly designed extrusion process, the workpiece has been heated to 550°C in the container. In addition, a combined heating process within the extrusion die has been realized without any necessity for using a heating chamber. FEM analyses have been conducted according to the flow chart given in Fig 3.

3. RESULTS

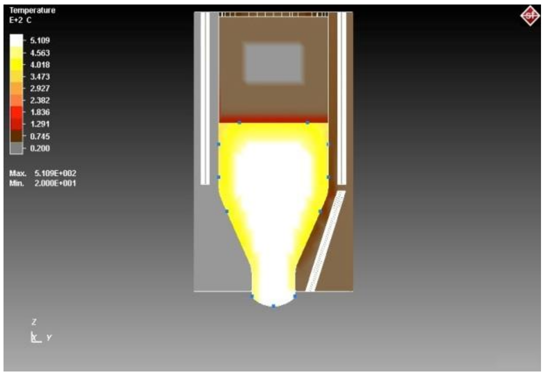
In conventional extrusion processes, obtainment of products possessing the desired mechanical properties and not exhibiting any deformation with the help of experience added by the operator or workers is very difficult indeed. In particular, the inability to adjust the temperature of the billet as required makes the process much more important. In order to avoid any change in mechanical properties after extrusion of Al6061 alloy, temperature of the billet should be within the desired range. In extrusion processes Both the electric power required for heating the container and the time consumed for the heating process itself raise the cost of the extrusion process at considerable levels. For this reason, in the case of Al extrusion process, the billet needs to be heated to the extrusion temperature in the container. In the model developed, a heating chamber with resistors which is combined with the container has been modeled (Fig 2.a-b). Thanks to resistors placed not only into the container but also at the outlet of the container (the area where the section gets narrower), the temperature can be kept fixed at the desired extrusion temperature. In FEM analysis, the extrusion process conducted with an unheated conventional container has been dwelled on at first, which was followed by a comparison of temperature, pressure, stresses and material flow within the framework of an extrusion process applied in the newly designed container.

3.1 Temperature variations

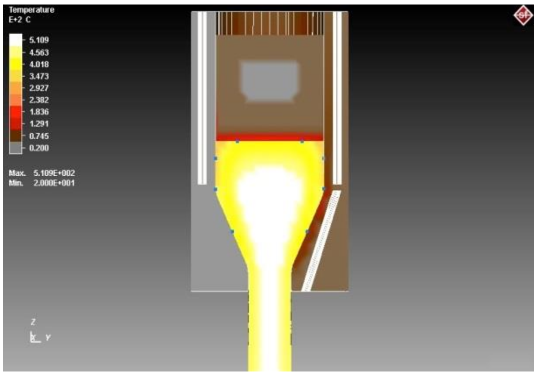
In conventional extrusion processes, two types of problems may be experienced during extrusion of the hot billet in the unheated container. The first problem is temperature rise because of plastic deformation in hot or cold extrusion process. When temperature values arising during extrusion process conducted by application of conventional methods are considered, it is observed that plastic deformation energy plays an important role in temperature rise [4]. If temperature which is desired not to exceed a certain degree rises above 600^{o}C, this situation may cause a change in mechanical properties of the extruded billet [15]. The second problem is that, though the workpiece in conventional extrusion process is heated to 550^{o}C, the billet cools down to 510^{o}C before commencement of the extrusion process [11]. It is observed that the temperature, with a deformation rate of 10%, declines down to 399^{o}C at points of contact with the container (Fig 4). Especially on the sides and outer walls that came into contact with the cold (or warm) container, heat transfer has occurred early wherefore temperature value has remained far below the extrusion temperature (Fig 4 a-b). As the level of deformation gets higher, temperature would normally rise to some extent because of deformation energy. However, despite this fact, it has been determined that there was a temperature drop in some areas (such as dead zone) (Fig 4.c). In fact, as Fig 4.b indicates, although the temperature in the billet was even with the extrusion temperature, it has been noted that the temperature declined down to 390^{o}C on the sides which were in contact with the container. It has been observed that, as the rate of deformation increased, temperature drops occurred not only at points where the workpiece was in contact with the container but also in its interior parts. While heat transfer was higher on the surface of the workpiece because of the temperature difference between the container and the workpiece, the rise in deformation rate has led to an increased heat transfer in the inner parts of the workpiece as well. At a deformation rate of 50%, temperature drop due to heat transfer has been clearly found. On the other hand, at a deformation rate of 90%, the temperature of almost the entire workpiece has dropped to about 418^{o}C. In other words, extrusion process which was started at a temperature of 550^{o}C has been finished at 418^{o}C. When the process was completed, temperature difference between the interior middle part of the workpiece and its surface was 120^{o}C. In the case of the newly designed container, temperature of the resistors and that of the container were kept fixed at 900^{o}C and 550^{o}C respectively. The billet was heated in the container without the necessity for application of any heating process or use of any heating chamber, and the process has been completed accordingly (Fig 5 a.b.c). Temperature of the billet which was heated in the container was 550^{o}C. Since the container and the billet had the same temperature (550^{o}C), heat transfer has occurred at a low rate (Fig. 5.a). Although no temperature variation was experienced during the process which began at 550^{o}C, somewhat an increase (+20^{o}C) has been observed because of plastic deformation energy. Namely, extrusion process that was started at 550^{o}C has been finished nearly at the same temperature.



a.



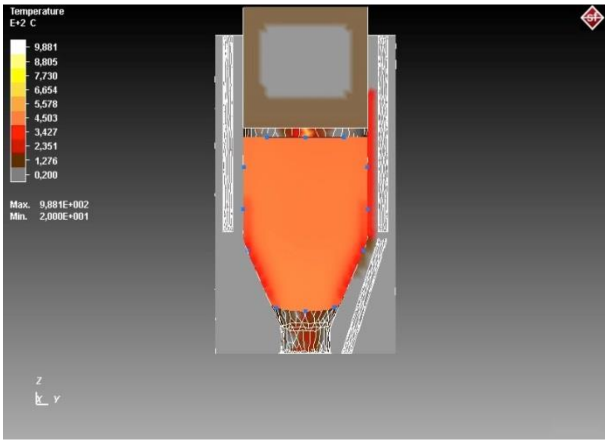
b.



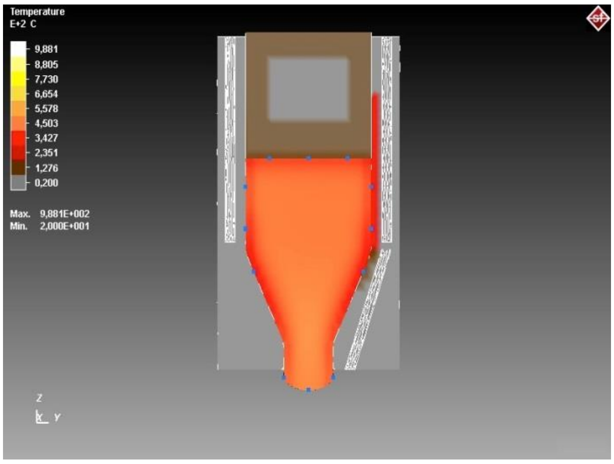
c.

Fig 4. Temperature variations occurring in the billet during the extrusion process (unheated container)
a.30% deform. b. 50% deform. c. 70% deform.

Our new design has ensured that the extrusion process is completed at the same temperature with that prevailing at the commencement of the process. Hence, thanks to our new design, potential dimensional defects and thermal distortions as well as changes in internal structure may be avoided. That is to say, extrusion process has been conducted and completed as desired. With a view to understanding the temperature change that occurs in the billet in the case of unheated container, temperature variations taking place at point nos. 1, 3 and 5 on the billet throughout the process have been investigated. In unheated container, it has been observed that the temperature declined in areas which underwent treatment and that such temperature drop was more significant at point no. 5 (Fig 6). Since the container was not heated, Fig 6 shows that the temperature of the workpiece which entered the plastic deformation zone has substantially dropped. Even though an increase in the temperature of the workpiece was concerned because of plastic deformation, a temperature drop has been noted in the billet that came into contact with the cold container.



a.



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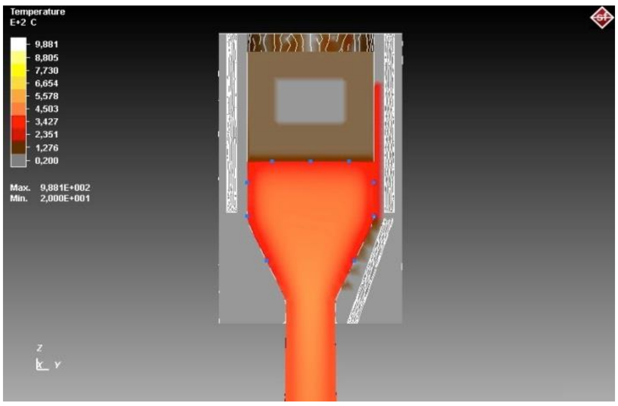

c.

Fig 5. Temperature variations occurring in the billet during the extrusion process (heated container + workpiece)
a. 30% deform. b. 50% deform. c. 70% deform.

When speed of the ram gets higher, temperature increases on account of nonuniform pressure and resultant variations in friction [17]. According to our new model, heating of the container has substantially homogenized pressure distribution on the billet thereby preventing excessive, disproportionate rise of temperature.

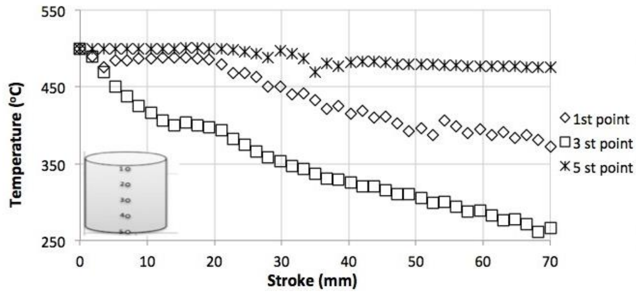

Fig 6. Temperature variations occurring at point nos. 1, 3, 5 on the billet in the unheated container

This situation points out that deformations or distortions may occur due to temperature differences thereby preventing successful completion of the extrusion process. While the temperature difference was around 200^{o}C in the case of unheated container, no temperature drop was observed in the case of heated container thanks to plastic deformation energy. In other words, extrusion temperature has been maintained, and, indeed, has even increased by 10%. As the container was kept at extrusion temperature, temperature change that occurred has increased the temperature of the billet (Fig 7). Our new design may also help avoiding deformations or distortions [16] that are likely to arise during extrusion of complex parts due to temperature differences occurring in production of T, H and L profile sections in particular. There is also an important connection between ram velocity and temperature variation.

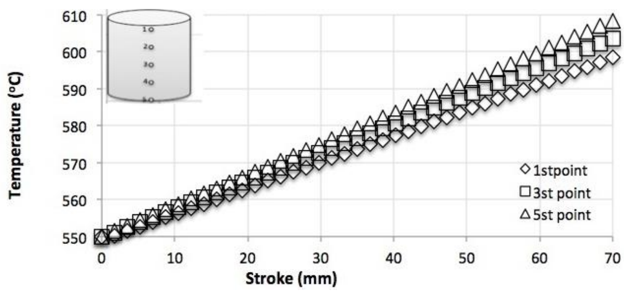

Fig 7. Temperature variations occurring at point nos.1, 3, 5 on the billet in the heated container

In the case of conventional methods, the extent of temperature change exhibits great variations especially in dead zone and plastic deformation zone [18]. For an extrusion process conducted at 300^{o}C, this variation appears as a temperature difference at the rate of 35%. However, in our newly designed model, such difference has been kept at a value below 5%.

3.2 Pressure

So that extrusion defects such as folding, etc. may be avoided and a proper material flow may be achieved, pressure must be distributed on the billet in an appropriate and proportionate manner. On most occasions, pressure cannot be distributed on the billet proportionately due to friction and temperature differences. Pressure is higher in the plastic deformation zone between the die and the workpiece and also at points where the punch contacts the workpiece. In the case of unheated container, it is observed that pressure force acting on the workpiece also increases. It is a fact that this pressure is influential in the plastic deformation zone [19-20]. Pressure force starts at approximately 32 MPa and increases up to 294 MPa, and, as the level of deformation gets higher, pressure value reaches the maximum level. In the entire workpiece, it has been noted that the pressure value climbed up to 294 MPa in the case of deformations above 30%. As for the extrusion process conducted in the heated container, it has been determined that strain value was around 13MPa in the first 25% portion of the deformation. This pressure force which was 30 MPa at 30% deform. has increased to 89MPa at 50% deform. and 95MPa at 70% deform. Maximum pressure applied was 114.7 MPa. It has been observed that pressure variations which occurred on the billet when passing the punch and the workpiece narrow section were lower as compared to those in the unheated container. Narrow section outlet pressure which was in the range of (40-58)MPa in the heated container has been found as 250MPa in the case of unheated container. Maximum pressure which the billet underwent has brought along a big difference between two models. In unheated container, pressure has tended to increase constantly as the temperature of the billet continued to drop throughout the process. After 20% deformation, the pressure has shown a sharp increasing trend up to 294MPa. In the case of our new model where both the container and the billet were at extrusion temperature, pressure deformation curve has demonstrated a sharp increase up to 60% deformation value and reached nearly 90 MPa. On the other hand, after this deformation value, only slight increases which ended up with 114.7 MPa have been observed. Fig 8 indicates that extrusion pressure difference between heated and unheated containers was more than 100%. This big difference also means that the necessary punch force is quite low wherefore the billet can be extruded at lower pressures.

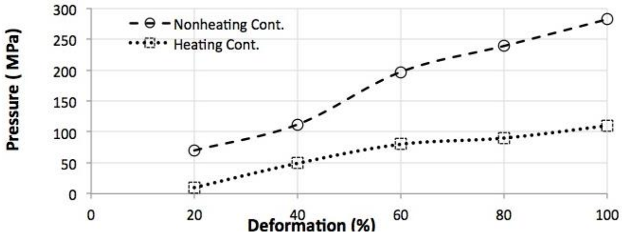

Fig 8. Variation of extrusion pressure in heated and unheated containers

3.3 Yield Stress

With regard to extrusion conducted in unheated container, yield stresses obtained as a result of analyses are shown in Table 2. As expected, yield stress increases in line with the increase in the level of deformation. Temperature difference between the container and the billet leads to an increase in stresses. During extrusion process, friction force between the billet and the container is quite high. With a view to reducing this friction force, lubricating and heating both the container and the billet may be considered as an additional measure. Because of the contact between the container and the billet, stress values in the entire billet are around 57 MPa at 30% deformation. In the case of heated container, stress value on the sides of the billet has been determined as 50MPa at 30% deformation. These values have been observed at points where the billet came into contact with the container. In other parts of the billet, average stress value is around 40-45 MPa at 30% deform. This difference is notable in the case of other deformation rates as well. It has been observed that such stresses are much lower in heated container. Wear life of the container will be higher if the stresses which the container undergoes are lower.

Table 2. Yield stress occurring in the billet in the case of resistance container and unheated container

Deformation	Noneheating Container	Heating Container
%30	57 MPa	50 MPa
%50	80 MPa	60 MPa
%70	115 MPa	80 MPa

Therefore, this process also bears significance in respect of the possibility to prolong wear life of the container. Stress values have proved to be higher in the case of extrusion process conducted by application of conventional method. As the rate of deformation gets higher, stress value changes by around 40% (Fig 9). Stress values that varied by nearly 10% up to 40% deformation have changed by almost 100% when the rate of deformation increased more and more.

3.4 Metal Flow Rate

Controlling the rate of metal flow occurring during the extrusion process is very important in terms of obtaining a defect-free product. If flow rate is not stable, folding may occur in the workpiece. Nonetheless, variations in friction force during the process appear to be a critical factor influencing the flow rate. In the case of unheated container, extrusion process has started at a metal flow rate of 62.6 mm/s which subsequently rose to 187.7 mm/s in the narrowing section at 40% deformation. On the other hand, such flow rate has reached 438 mm/s at 60% deformation. It has been observed that metal flow registered a notable increase in the plastic deformation zone. In the case of heated container, rate of metal flow was 60 mm/s in the beginning and followed a quite stable and regular trend. Such flow rate has reached 250 mm/s at points where the section got narrower.

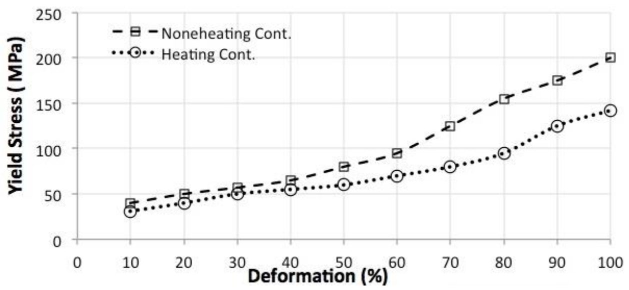

Fig 9. Stress values developing in the billet according to conventional and new container designs

4. CONCLUSIONS

In our study, a new extrusion container has been designed and modeled by means of which deformations or distortions occurring due to heating problem can be minimized and an end-product possessing desired mechanical properties can be obtained. Superiorities of this model -which was realized by the help of FEM analyses- over conventional practices, are enumerated below:

Required billet temperature of 550^{o}C, which qualifies as the necessary extrusion temperature for Al6061 alloy, is normally difficult to adjust and maintain in cases where conventional methods are applied. However, thanks to our new design, it has been possible to easily maintain the billet at this temperature. Even though the temperature of the billet entering plastic deformation zone increases due to the effect of deformation, it is also a fact that such temperature drops because the billet is contact with the cold container. Temperature difference between upper and lower points of the billet is approximately 200^{o}C. In other words, rate of temperature drop is 50%. However, in the case of extrusion process conducted by use of the newly designed container, we managed to keep the temperature difference at around 10% only. Fall of temperature below extrusion value is an inevitable outcome in processes that are conducted by application of conventional methods. This situation changes mechanical properties of the end-product as well. Holding the opinion that our new design would cope with this disadvantage, we established our model with a view to maintaining the billet temperature at the extrusion temperature. Accordingly, our new model has proved to be successful in keeping the billet temperature at extrusion values. In conventional methods, the billet which is first tempered in a furnace and then put into the unheated container is reheated to extrusion temperature by placing the container in a heating chamber before commencement of the extrusion process. This procedure causes waste of energy and time. However, according to our new model, the process concerned is conducted at a single step and in a controlled manner. Therefore, we hold the opinion that our model would ensure the saving of time, labor and energy. In conventional methods, pressure that develops during extrusion process is not homogeneously or uniformly distributed on the billet. In this case, deformations or distortions occur in the end of the process on account of friction between the container and the billet. By adjusting the temperature of the container and hence keeping the billet at extrusion temperature, we have ensured that the pressure is proportionately distributed on the billet. This, in turn, has enabled the avoidance of undesired deformations. Our newly designed resistance container has helped minimizing stresses thereby ensuring a homogeneous distribution on the billet. So that a homogeneous and uniform deformation may be achieved during extrusion, there should be a homogeneous metal flow on the billet. In conventional applications, it was attempted to carry out this process mostly by the help of container design. However, our study has clearly demonstrated the adverse impact of temperature. For this reason, our new design which involved maintenance of the billet at the extrusion temperature has eliminated subject disadvantage by realizing a homogeneous metal flow on the billet. In extrusion process, impact of pressure force on the end piece is very important. In the case of extrusion process conducted by use of unheated container, pressure has increased to 294 MPa. However, thanks to our newly designed resistance container, the same process has been realized at a pressure level of 114.7MPa only. Namely, extrusion process has been completed by applying a much lower pressure. In consideration of the foregoing items, we may surely deduce that our new design would minimize labor costs, prevent waste of material, and ensure the saving of energy. In conclusion, cost of end-product will be reduced at a considerable extent. In FEM model, it has been observed that the temperature of the billet which measures 366cm^3 in volume rose to extrusion temperature (550^{o}C) in 30s.

In an effort to improve this model further, changes in microstructure may be studied at later stages, in connection with variations in temperature and other parameters. The model may be further developed so as to ensure that the heating process, along with the resistors, is conducted in a fully automated and computer-controlled fashion.

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