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論 文 内 容 要 旨

In the hot-extrusion process, products with complex cross-section can be fabricated from cylindrical billets only in one step. In addition, inhomogeneous and coarse cast-structure of billets is transformed to fine microstructure during the process. Therefore, extrusion is the indispensable process for net-shape or near net-shape working of aluminum, magnesium, copper, titanium, iron and their alloys. But on the other hand, giving a large reduction of area in one process not only requires large forming pressure, but also results in inhomogeneous metal flow. Excessive forming pressure leads to plastic deformation or failure of tools, and inhomogeneous metal flow causes various product defects, that is, poor dimensional-precision, curling, twisting, inward flow of contaminated surface, tearing, cracking and so on. For this reason, a number of attentions have been given to improvement of extrudability. Die design is the most dominant factor which decides quality of extrudates and producibility. Therefore, many experimental and theoretical plasticity analyses have been developed for years.

Although, variety of different fields in die extrusion design and analyses have been covered by previous researchers, however more attentions need to be given to metal flow pattern in flat face die of different sections in extrusion. Specially when extrusion of materials with low flow stress is concerned, flat face die needs more attention. Because from economical point of view, this kind of die has upper hand in these cases.

As will be shown after, the comprehensive study on metal flow pattern from entrance to exit section has led to realizing an interesting and important phenomenon. The initial round-section firstly changes to an intermediate shape of deformation zone which is circular or elliptic, and after that, the intermediate section changes to the final exit-section, independent of the location of die exit hole. The existance of the intermediate deformation zone has been observed commonly in extrusion of U-, H-, L-, h-shaped products.

In this research, extrusion of "U" section from a cylindrical billet has been analysed as a representative example of channel bars. "Flat-face die" has been used with complete attention to metal flow pattern from entrance to exit. Because, as mentioned before, nothing but flat-face die is used in practical extrusion of non-ferrous metals and alloys. Numerical analysis has been done based on upper bound approach, and the effect of the occurrence of the intermediate deformation zone on the extrusion pressure has been estimated. The analytical procedure adapted in this study is applicable to not only extrusion of differently shaped channel bars through flat-face dies but also design of stream die for materials with high flow stress.

1-Macrostructure of Metal Flow Pattern

For conduting this research two kinds of U sections have been considered. In one die the length and height of U section are different, and in the other one, they are equal. Experimental results of metal flow pattern of extrusion from round billet to exit section of two kinds of U sections have been shown in Fig.1 and Fig.2. As can be seen in these two figures, the entrance section changes to exit section through either eliptic (Fig.1) or round (Fig.2) intermediate deformation zone. In the other words, there is not any sudden change from entrance to exit section. This is an important phenomenon. The effect of die exit configuration on metal flow pattern can be noticed in these figures.

When the length and height of exit section are different, the elliptic intermediate deformation zone appears between entrance and exit section (Fig.1). When length and height of exit section are equal, deformation process includes round intermediate section (Fig.2).

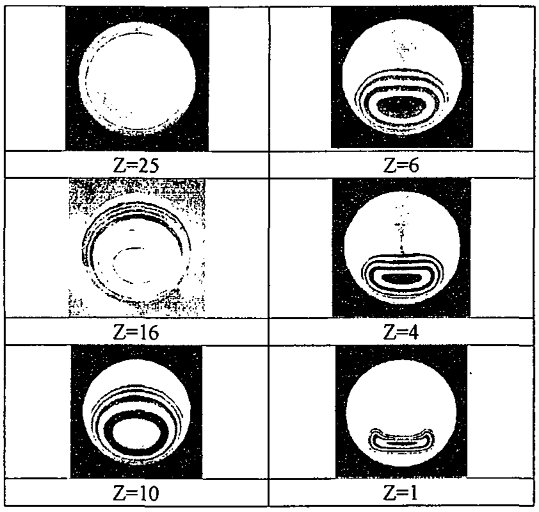

Fig.1-Experimental results of metal flow pattern through elliptic intermediate section

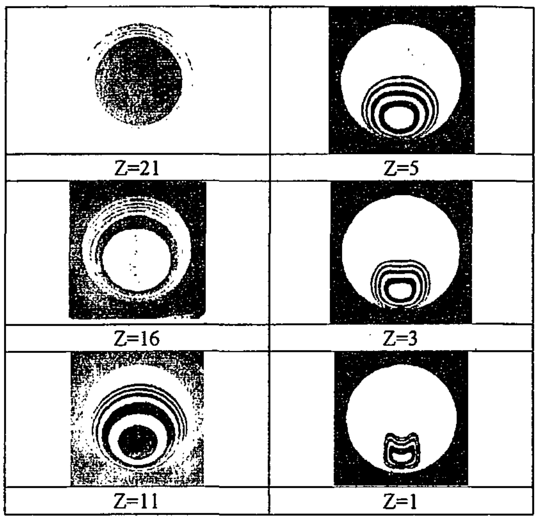

Fig.2-Experimental results of metal flow pattern through round intermediate section

As can be seen, after starting the deformation in plastic region, shear plastic layers are observed due to high friction on the container and gradually dead metal zone appears (white area) and then developes step by step, until deformation reaches to final step.

Since we have used flat face die, metal flows freely for making the dead metal zone without any restriction from entrance to exit section. So metal flows in a such way that the deformation energy of the whole process will be minimized. This is the case for every natural process in which there is not any restriction. Appearing intermediate section of deformation zone between entrance and exit section satisfies this natural law.

With considering either elliptic or round intermediate section of deformation zone, the whole deformation process will be devided into two parts. From entrance to intermadiate section, and from intermediate section of deformation zone to exit section.

It is obvious that without considering optimum intermediate section of deformation zone, we are unable to simulate metal flow pattern. Because there can be many intermediate sections of deformation zone, and only one of them minimize deformation energy in the whole process from entrance to exit section. So different kinds of intermediate sections have been considered, and by upper bound method deformation energy in the whole deformation process for each of them has been obtained.

By upper bound approach, deformation energy of the whole process for different elliptic intermediate section, have been calculated. Therefore, optimum minor and major radius of intermediate elliptic section of deformation zone (a,b) are obtained. At these optimum values, the deformation energy will be minimized.

The optimum relative major and minor radius of elliptic intermediate section of deformation zone are as follow: $a/r = .6$ and $b/r = .733$, where r is the radius of entrance section.

The upper bound results show that when major and minor radius of elliptic intermediate section appraches to radius of entrance section, the energy of whole deformation process will highly increase. This means that intermediate approaches to entrance section and there is no intermediate section. Therefore, any direct and sudden change from entrance to exit section will increase energy of deformation. Another important issue is that in all different kinds of intermediate section of deformation zone the elliptic shape will have the minimum energy, rather than round shape.

Also the similar analysis has been done for the second die, in which length and height of exit section are equal. In this die, round intermediate section appears between entrance and exit section. Similarly by upper bound method the deformation energy in the whole process for various intermediate sections has been obtained. In this case, the optimum intermediate section has been $a = b = .533r$.

An interesting point is that with considering intermediate section of deformation zone the deformation energy will be decreased. Also deformation energy of the whole process at optimum round intermediate section of deformation zone,will be minimized. Upper results show that the whole deformation energy of the sudden change from entrance to exit section without considering intermediate section will be more than double in comparison to minimum energy with optimum round intermediate section.

Also analytical results of extrusion pressure in both dies is about 15% higher than experimental results which is quite reasonable in upper bound method.

2-Simulation of Metal Flow Pattern

Now with optimizing the intermediate sections of deformation zone, ellipse and circle, in two different dies, metal flow pattern can be simulated. Simulation for the first die with elliptic shape of intermediate section is shown in Fig.3.

As shown round shape changes to exit section through an elliptic shape as an intermediate section. This simulated smooth transition is completely confirmed by experimental results of metal flow pattern.

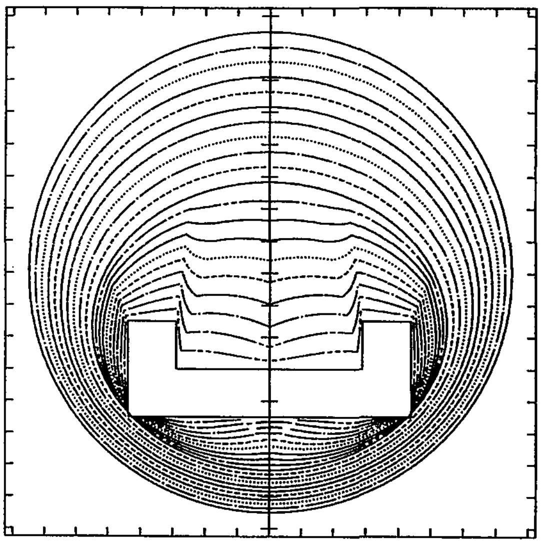

Fig.3-Cross sections of deformation zone at different levels with ellipse as an intermediate section

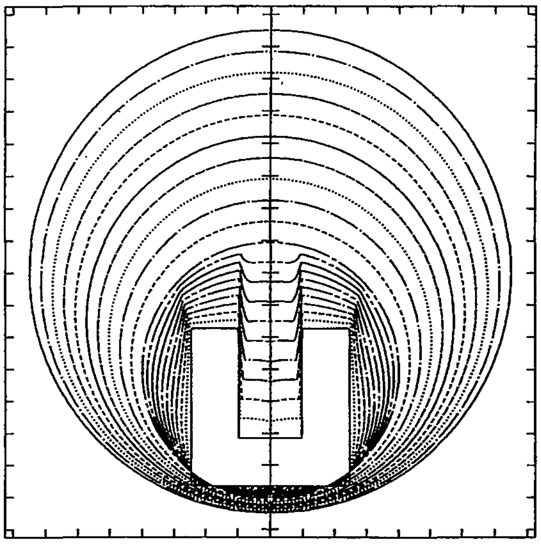

Fig.4-Deformation zone at different evaluations with round intermediate section

Also simulation of metal flow pattern for the second die with round intermediate section of deformation zone is shown in Fig.4. As can be seen this simulated metal flow pattern is completely comparable with experimental results.

3-Conclusion

Intermediate section of deformation zone will play a key role for determining and calculating energy in the whole deformation process. It may bring about a huge difference in calculated energy in the deformation process whether the occurrence of the intermediate deformation process is taken into consideration or not. It is evidently supposed that ignoring the intermediate section of deformation zone between the entrance and exit sections will highly increase energy in the whole process.

Die exit configuration affects metal flow pattern from round entrance to exit section. When height and length of exit section in extrusion of U section are not equal, elliptic section and when they are equal round section appears between entrance and exit section. This optimum intermediate section of deformation will minimize energy of the deformation process.

審査結果の要旨

押出し加工は、一工程で単純断面形状から複雑断面形状への加工ができる汎用性の高い加工法であるが、反面、材料流れが複雑になるために形状不整が生じ易く、ダイ設計・製作にあたって熟練者の経験と試行錯誤に依存する部分が多い。著者は、異形断面形状材の押出しにおける変形域形状変化を丹念に追跡し、多くの場合、一端楕円形状の中間変形域を経て、最終形状に至るというダイ設計に資する新たな知見を得、解析を通して２段階の変形過程の方が所要変形エネルギが小さいことを明らかにした。本論文は、この研究成果をまとめたもので、全編６章よりなる。

第１章は序論であり、本研究の背景と目的について述べている。

第２章は実験方法を述べたものであり、特に、押出し過程における材料流れを調べるための幾つかの手法の短・長所に言及し、それらを併用することの必要性を述べている。

第３章では、異形断面チャンネル材の代表例として凹形を取り上げ、リム高さと底辺長さが等しい場合について、押出し過程における変形域形状変化が初期形状から円形の中間変形域を経て最終形状に至ることを実験的に示す一方で、上界法に基づく解析より、初期形状から直接最終形状に至るよりも２段階変形過程が所要変形エネルギを小さくすることを示している。

第４章では、凹形形状のリム高さ／底辺長さ比が１以下について同様の検討を行い、この場合には、中間変形域形状が楕円になることを示し、さらに、同一形状であってもリム部と底辺部の肉厚が異なれば楕円の短軸／長軸比が異なること、他の断面形状でもそれぞれの形に依存した短軸／長軸比をもつ楕円状の中間変形域を経ることから、このような２段階変形過程が異形材押出しに共通した現象であることを述べている。

第５章では、押出し荷重及び押出し材の曲りに及ぼすダイ孔位置の影響を上界解析から見積もり、荷重を最小にするダイ孔位置と形状不整がないダイ孔位置とは異なることを示し、工業的に多く採用されている平面ダイを用いる場合、フローガイドを適切に設計することにより、形状不整がなく、かつ押出し荷重を低減することが可能であることを示唆している。

第６章は結論である。

なお、最後に、付記として本研究で採用した三次元上界解析の詳細をまとめている。

以上要するに、異形材の押出し加工における材料流れが、従来想定されていたものとは異なり、一端、楕円状中間変形域を経て最終形状に至ることを、実験及び理論解析の両面から、明らかにしており、平面ダイを使用する場合のフローガイドの設計あるいは曲線ダイの設計に対する指針を与えるものであり、加工プロセス学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。